

Simulation and Analysis of Particle Flow Through an Aggregate Stockpile

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Abstract

For many aggregate mining facilities, the stockpile is the preferred method of storing rock. In many aggregate mines, as well as other mines using stockpiling techniques, understanding the timing and flow of particles through a stockpile is important for correctly timing samples, making proper process adjustments and overall stockpile safety. Because much of the research of today lacks important information regarding actual interior particle movement within a stockpile, a series of Real Time Distribution (RTD) analyses and stockpile flow models have been prepared and analyzed for this study in order to better understand the flow characteristics of a stockpile.

A series of three RTD analyses performed on three separate stockpiles provides information leading to the assumption that stockpiles tend to operate similar to a plug flow system. While conveyor loading techniques may lead to separation of rocks prior to traveling through the stockpile, the majority of the rock particles entering the pile remain near the point of entry, or within the “action” area, and will travel through the pile in a plug flow, rather than a mixed flow, manner. High Peclet number results for each analysis prove this assumption to be accurate.

A series of models on three separate stockpiles have been created using PFC3d. Mainly, the simulations prove PFC3d is capable of showing how stockpile particles move in three dimensions while monitoring specific particles within the pile. In addition, these models provided simulation results similar to the results obtained within the RTD analyses. Results show that particles located directly above the discharge point, or “action” area, travel through the pile at a faster rate than particles surrounding this area. Velocity results obtained from the simulations show particles accelerating as they get closer to the discharge points while also providing evidence of “arching” during the simulation process. These findings provide a better understanding of internal flow within the stockpile and ways to possibly predict future stockpile flow issues that may be encountered.

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Chapter 1: Introduction

1. General

Stockpiles are used in many applications within the mining industry. A simple design, usually associated with little moving machinery, it is an essential part of most mines. In the coal industry, stockpiles are primarily usually used as short or long term storage. The metals industry sometimes uses stockpiles as leach beds, with the design and proper layout of the stockpile being very important. The fine sands and minerals industry uses stockpiles as both a storage and discharge location with a feeder usually located beneath the pile. The aggregate industry is similar in that it also uses stockpiles for storage and discharge purposes, but with larger material.

The geometry of a stockpile varies according to the type of material being stored and the environment the pile is in. The angle of repose, or the angle at which the material makes when allowed to settle, usually remains consistent around the base of the pile. Various environments can cause many geometric changes to the stockpile. Such changes include slumping and sliding along the base due to heavy rain and stockpile deformation due to heavy wind. The following Figure shows the general shape and design of a stockpile (LuckStone 2005).



Figure 1.1 - General aggregate rock stockpile

Stockpiles are used throughout mining over other storage methods because of the various loading/unloading techniques and the ability to actually store the rock using this method. Silos, and other storage devices, are an unnecessary added cost which is needed only if the material to be stored is toxic, flows freely, or requires a special discharge technique. Stockpiling also eliminates additional maintenance brought forth by corrosion and general wear and tear.

In the case of aggregate mining, stockpiling is the number one method of storing rock. Stockpiles are used within the plant process primarily as short term storage. Discharge tunnels beneath the stockpile constantly remove rock from the pile to be taken to other locations within the plant. This is usually happening while the stockpile is also being loaded by a conveyor. Stockpiles are also used as short to long term storage of final product. Each product size usually has its own pile where a front-end loader can easily load drive-up trucks at any point around the base of the pile.

2. Purpose of Research

While stockpile storage of aggregate material is preferred within the aggregate industry, little research has been done on stockpile flows. In the case of aggregates, sampling the discharge of stockpiles is important for quality control and when specific tests are needed to rate performance. Sometimes stockpile feeding or discharge adjustments can be very difficult to accurately perform and can skew data or cause excessive wait time in order to assure a sample of a specific rock. There are also instances where various changes in rock hardness and size can manipulate a plant or cause damage to various parts of a plant. An overall better understanding of rock movement and general flow through a stockpile would provide knowledge to perform proper tests and improve overall mine efficiency.

In cases outside of aggregate mining, stockpile flow research would also provide a better understanding in quality control and safety. In terms of control, understanding when various ore types are within a pile would allow for proper adjustments at the processing plant. For instance, knowing when random changes in oxidation levels would be entering a processing plant would allow for proper adjustments. Stockpile flow research could also assist in understanding bridging and ratholing. From 2000-2007 there were 49 reportable injuries related to the climbing of piled material alone (NIOSH, 2009). Considering there were additional accidents related to stockpile flow and feeder issues, it is evident that many dangers exist while working on or around stockpiles. Understanding these issues would allow for preventive procedures to be developed to reduce stockpile accidents.

3. Structure of Research

This research discusses the attempts to prepare a Residence Time Distribution (RTD) analysis on a discharging stockpile based on various introductory methods and the use of distinct element method to simulate particle movement through a stockpile. Both of these research topics will include a summary of program and field work preparation and a discussion of the results determined after the simulation and analysis have been completed. Final simulation results hope to provide a better understanding of how rocks react within a stockpile during discharge from beneath the pile. A completed RTD analysis hopes to provide a better understanding on how introducing material to a pile can affect the quality of material discharging from the pile. While the results may not provide answers to all stockpile related issues and questions, the results should provide a foundation for future research.

Chapter 2: Literature Review

1. Literature Introduction

The scope of stockpile research is very limited in terms of particle and rock flow. The following review will discuss the various simulations performed on stockpiles and research necessary in the completion of this paper. Past research was limited to quality control, safety and particle interaction. Stockpile flow research is either non-existent or extremely limited. For this reason, some hopper flow research and research lacking flow content was reviewed in order to understand the importance of particle flow. The stockpile flow research which will be covered in this thesis will relate to all of the research included in this literature review. The understanding of how particles flow in a pile will hopefully assist any future research of the stockpile.

2. Discrete Element Method

Numerical methods for computing motion of objects are used in many research applications today. Some methods focus on the problem as a holistic, or continuum. Other methods focus on many tiny pieces within the system in order to represent the system in a model. Discrete element method (DEM) is a numerical method for computing motion of a large number of particles that represent a system.

DEM was first applied by Cundall in 1971 in order to address issues in rock mechanics (Cundall and Strack 1979). Cundall's other early studies more focused on microscopic and macroscopic characteristics of many tiny discs. In one paper, the behavior of soil was modeled (Cundall and Strack 1983). This was a 2D model that mainly determined material behavior after applying many different exterior boundary conditions. The program Cundall used during this time was titled BALL. This program appears to be much like the simpler 2D DEM programs used today.

Williams, Hocking and Mustoe in 1985 explained that DEM was more of a generalized finite element method. This is true in that DEM looks at the individual particles within the system and provides data according to each individual sphere or circle. Finite element method breaks down objects or flows into many small spheres or circles, but only does this to relate to the system as a whole. Finite element method is more of a continuum model while DEM treats each particle within the model as its own, or as many tiny finite elements (Williams, Hocking et al. 1985).

While DEM uses spherical or round particles in its models, the method is actually capable of modeling particles with non-spherical shape. This is usually done so by grouping or bonding many particles together to represent a random mass. This is extremely useful in many flow applications where non-spherical particles are present.

Discrete element models are very detailed models that usually require a lot of computer power. Because each particle is treated as its own and has its own set of data, the model usually is limited to a specific number of particles. While advances in software are beginning to take place, some programs with many of thousands of particles still need a quick processor (Yasar, Kuraoka et al. 1997; Wikipedia 2006).

Considering DEM models can take many separate, discrete particles and shape them for use in many different experiments, it is very useful in many fields. DEM is sometimes used in liquid applications where the particles are given parameters that allow the application to flow freely. Bulk materials are also modeled with DEM, such as with silo storage. DEM is also used in a more straight forward application such as with granular material and powder flow where each particle acts as a single grain of sand or powder. Each of these examples may represent an application used within many types of jobs. Though, DEM is more commonly used in mining, pharmaceuticals, oil and gas, agriculture and food handling fields.

There are many commercial and non-commercial DEM software packages that are available today. The original Cundall designed software, BALL, is non-commercial software and is one of the older programs available. Particle Flow Code in 3D, or PFC3D, is one of the popular programs used today. Considering it is in three dimensions, it is the most realistic of the programs and was used to develop the models in this thesis.

2.1. Particle Flow Code in Three Dimensions (PFC3D)

The numerical “Particle Flow Code,” or PFC, models sphere particle movement and interaction using the discrete element method. PFC can operate in either 2D or 3D. Calculations in PFC are taken over a series of time steps. This makes it easy on the computer memory in that dynamic equations are performed on every time step, rather than saving and reapplying matrices as in an implicit scheme. However, many thousand time steps are run, and calculations are done on each particle for each step. Considering each step is usually a fraction of a second, the program run time is rather lengthy. This can be an issue considering many applications require a large amount of particles to properly simulate a system (Lorig, Gibson et al. 1995; Itasca Consulting Group 2004).

A PFC3D simulation is started by developing a model outline. When first developing a model the schematics must be inserted. This includes any walls or particles that are necessary in representing the system to be modeled. Information can be inserted into PFC either through a command line or through an input file coded for PFC. Once all particles and walls have been properly inserted the program will run a series of cycles. Each cycle performs the specific calculations stated by the programmer and allows the particles to interact accordingly. After each cycle is complete, the computer takes the new particle data and starts a new cycle. The cycling is then repeated until the model is complete. Information requested can then be collected for analysis (Itasca Consulting Group 2004).

3. Associated Flow Research

3.1. Quality Control Models

While there is limited research on stockpiles and their internal flow, there is much research involving quality control. Quality control is important in controlling product and throughput for a plant. Understanding particle flow through a stockpile has a large influence on quality control. Most of the quality control research of today focuses on quality of what enters or exits a pile and ignores what goes on inside of the pile. The addition of internal flow research will assist in perfecting quality control.

Past quality control research, which more focuses on final product, lacks important information about what goes on within the pile. For example, P. Keleher's paper discusses how QMASTOR uses stockpile performance numbers to make proper adjustments to shipments (Keleher, Cameron et al. 1998). J.E. Everett discussed how simple adjustments to discharge rates and pickup timing can improve mine life and quality of product (Everett and Kamperman 2000). Similar to Everett's paper, M.L. Smith showed how production scheduling and inventory control can be controlled by proper discharge techniques (Smith 1999). Another example is seen in M.G. Nelson's paper where simulations were performed on random mine data in order to determine how to properly blend product using a real-time analyzer (Nelson and Riddle 2004). In each of these papers, final product was solely focused on while internal flow was ignored. The use of internal flow data within the stockpiles would have provided a more detailed understanding of how to both load, and unload, the stockpiles efficiently.

Perfecting blending techniques to control product has also been heavily researched over the years. Recent developments in simulation techniques have lead to a number of new papers relating to the topic. Along with Nelson's paper on simulating a real time analyzer are papers where simple visual basic programs are used to properly layout blending schemes. Francis

Pavloudakis used this technique in his paper to layout stockpile yards in ways that would properly blend material based on conveyor introduction to the pile. While this blending method did prove efficient, it lacked information on how the product blended while being discharged (Pavloudakis and Agioutantis 2003). The following figure presents how specified areas of flow react during discharge as depicted in an image from a paper by Prescott and Barnum titled “On Powder Flowability.” Having similar information could have led to an even better program for Pavloudakis capable of providing higher blending efficiencies.

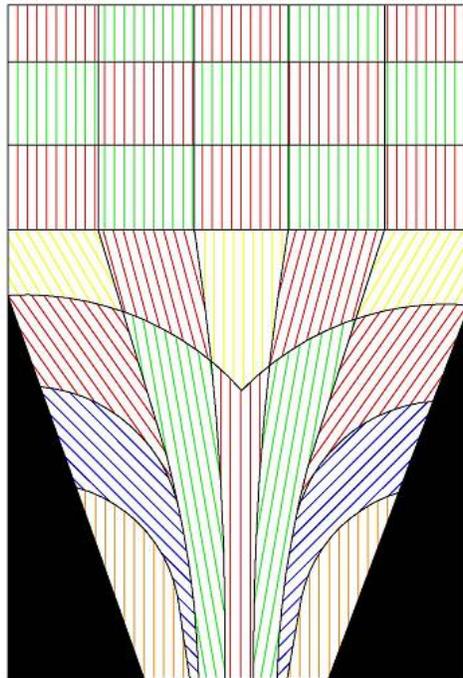


Figure 2.1 - Flow profile blending during discharge

Aggregate studies have proven that proper mine design and operation timing is important to maintain an efficient mine. Minestar, by caterpillar, is used in some mines today as an operational management system. The precise data capture of Minestar enables for better blasting, quarry control, exploratory drilling, hauling, etc. While this system mostly looks at the mine efficiency as a whole, it does control stockpile deliveries and blends. Automatic controls adjust flow and blending of stockpiles in order to produce the desired product (Snow and Cousland 2002). Once again, this quality control program only adjusts according to trial and error. There is no flow data that is captured or understood by the program.

G.K. Robinson analyzes blending results based on predictions and proper material introduction to the stockpile. While this paper similarly discusses blending based on various stacking methods, this paper focuses on blending material as much as possible before removing product from a pile. The stockpile model called “CHASM” was used to determine the results of

various stockpile stacking procedures. This program along with his research was able to predict variability of output based on predicted geometry and loading technique. In the research no flow data was actually needed to get an accurate stockpile output, however, Robinson did mention that output sampling theory was important to understanding the best possible blending that could be achieved (Robinson 2004). So while internal flow was negated, stockpile output was deemed important in determining the most efficient blending technique. Combining these parameters along with internal flow would have allowed a more accurate model.

Michael Binkowski approached the quality control aspect of stockpiling mathematically. The goal of his research was to develop a mathematical framework that would be able to model, analyze and optimize stockyard design. In other words, his research focused on finding the number and size of stockpiles needed to maximize throughput and cost at the mine. Using a series of equations, Michael was able to determine a method to optimize stockpile configuration so that the mine would operate more efficiently (Binkowski and Mccarragher 1999). Once again, ignoring blending during flow may have made this model slightly inefficient. Understanding how the material flows while leaving the stockpiles may have led to a different stockyard layout.

3.2. Granular Flow Studies

Another paper by a consultant at Jenike and Johanson discusses solid flow problems in bins, hoppers, and feeders. This paper states how walls in a hopper or bin that are too steep or rough may result in particle hang up, thus resulting in quality control issues (Marinelli and Carson 2001). In the case of aggregate stockpiles, this is evident, but is not as much of a concern. For instance, the stagnant rock within a stockpile acts as the walls of pile and resembles that of a silo. While stagnant rock in a silo may lead to excessive particle segregation and spoilage, stagnant aggregate rock in a stockpile is absent of these problems mostly because of the unimportance of aggregate rock remaining on the outside of the pile. The following figure compares a silo to an aggregate stockpile.

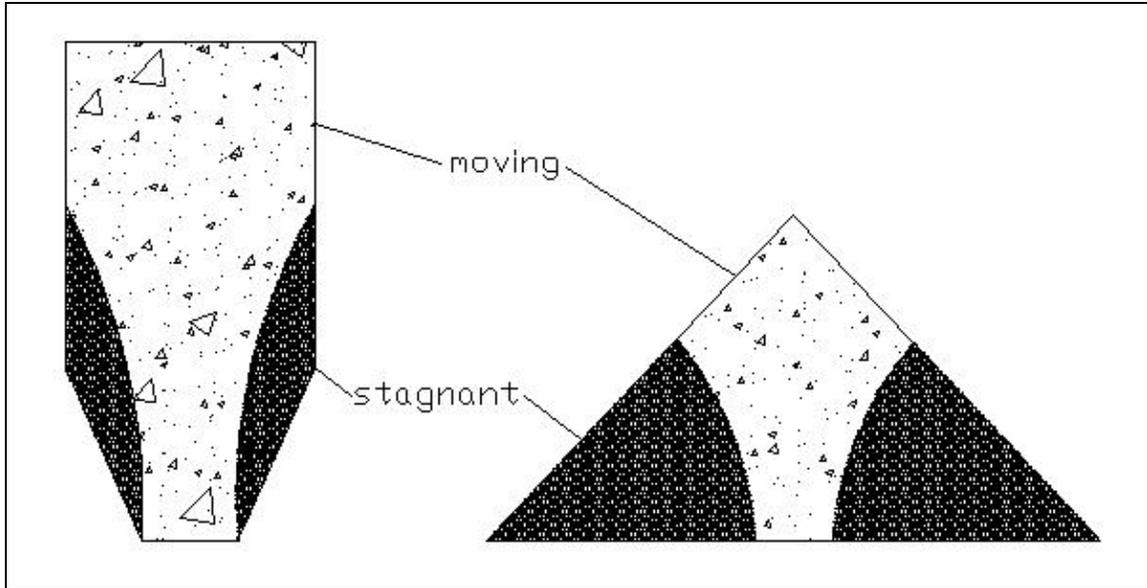


Figure 2.2 - Comparison of moving and stagnant material of silo and stockpile.

While issues of rock remaining stagnant around the lower boundaries of a pile have no effect on the quality of the pile, it does lead to arching within the pile. When the pile's discharge location gets smaller, the more capable it is of creating an interlocking arch. Maynard researched ways to prevent this from happening for cohesive fine material, but did not describe its effect on larger material (such as aggregate rock) (Maynard 2004). While arching has been witnessed to occur on occasion in aggregate mining, its effects on quality are mostly due to downtime. The bigger issue with arching is sudden collapses leading to cave-in and blow-out at the discharge point. This is of course a major safety issue that will be better explained later.

In order to obtain a consistent, even flow, proper dischargers must be used. Dischargers encourage the flow of material from a pile and cannot control the rate at which the material flows. Volumetric or gravimetric feeders are required to actually control rate and exist usually in fine material applications (Carson and Petro). In the case of an aggregate stockpile, only a discharger is used to assist in creating flow from a stockpile. This is mostly due to the size of the material.

Another stockpile flow issue is segregation. Segregation of particles within the stockpile has been a quality control issue in mining for many years. Overall, segregation occurs over a wide range of mining applications, though in coal it is especially evident. This is because coal tends to have very fine material blended with larger particles in order to create a required product. This usually occurs on a stockpile, where one material is blended with another while being presented to the pile. This is where sifting occurs. Sifting is simply the movement of finer particles through a mixture where larger particles are present. Sifting usually leads to a gathering

of smaller particles closer to the center of the pile (Carson, Royal et al.). While there are many methods used today to help prevent this, it tends to be ignored in the aggregate industry. This is mostly because the stockpile discharge goes through a crusher or series of screens before being declared product.

3.3. Flow Safety Research

While “ratholing” and internal voids are more of a common quality control problem in the fine materials industry, they can be very dangerous in the mining industry. P.C. Arnold performed research on the flow of fine coal stockpiles (Arnold, Fielder et al. 1983). His research examined the need for a better feeder, or discharging system beneath the pile. Earlier reclaim tunnels had a feeder design that had low recovery and produced “ratholes” and voids. These voids were dangerous in that they were capable of collapsing while dozers were mixing on the pile. In aggregate mines, there is also the danger of a sudden release of energy at the arch creating somewhat of a “rockburst.” The research eventually led to a feeder design that produced a 90% increase in recovery and the elimination of stockpile voids and “ratholes.” Future flow research would be able to determine well ahead of time when this problem was occurring and possibly locate the problem within the pile.

Other safety research is usually associated with displacement of piles and the results associated with displacement. B. A. Quinn (1995) had an article which more focused on the displacement of a stockpile due to fines. He performed lab tests to determine whether excessive fines and lack of medium sized particles can cause a decrease in stockpile slope stability. His results showed the changes in shear strength of a stockpile at different layers as a result of fine coal percolation and wet conditions. As a result of this research, stockpile instability was better understood and better methods of calculating factors of safety for stockpiles were determined. Some of the tertiary or secondary stockpiles within the aggregate industry may take on similar risks during wet conditions.

3.4. Flow Simulations and Models

Models simulating flow of granular material are developed to determine how particles interact while flowing within a system. Most of the simulations are done using distinct element method. The following papers use various techniques and methods to simulate flow and particle interaction within a system. While no stockpile flow research was found, many papers simulating silo flow were found. These papers were used to gain a general understanding of flow in a system similar to that of a stockpile.

A study which led to successful results on flow within a hopper was reviewed by P.A. Langston (Langston, Tuzun et al. 1995). This study described the results of a distinct element method simulation of hopper flow. Using a simple hopper design, similar to the simple stockpile design used to simulate in this paper, Langston was able to develop accurate velocity, contact forces and mass flow. The real purpose of his paper was to determine whether this exercise was more of a research or design tool. At the time of this paper, he concluded that the results were better used as a research tool until a more user friendly design was available in the future. At this point in time, there still exists no user-friendly design, and all flow research using distinct element method mostly goes into research and development. However, some companies do use very detailed models to assist in equipment design (Metso 2006). Due to the limited stockpile flow studies, this paper should be deemed an introduction to the subject and thus used as a tool for future research.

A similar successful hopper flow study was completed by H.P. Zue in 2002 (Zue and Yu 2002). In this paper, Zue stated that granular flow can be classified into two categories: macroscopic and microscopic. The macroscopic approach is more of a continuum approach which relies on a series of boundary conditions that balance out a model. The microscopic approach is more discrete and is based on the analysis of individual particles. This method is a more accurate way to describe flow because of its focus on individual particles. However, it usually requires many particles and can lead to an extensive program. Zue's research has determined a way to link microscopic variables in the discrete approach to macroscopic variables. By averaging microscopic results at a probe point a macroscopic solution is determined. This method was validated on a hopper where averaged stress components were compared to actual stresses within a hopper (Zue and Yu 2005). This method best represents how PFC determines macroscopic variables like velocity and stress within its model. Zue's method averages after DEM has been completed while PFC actually averages within the program. With this being understood, flow results calculated similarly through PFC can be deemed accurate when estimating velocities and flows of granular material.

It is believed that the used of conglomerated particles within PFC best represents rocks and other randomly sized particles. For example, L. Li used PFC2D to represent angular grains to realistically simulate the behavior of cemented granular material (Li and Holt 2001). While monitoring rock breakage was a factor in Li's experiment, it still proved how the use of conglomerated particles best represented an actual particle shape. Similarly, Hamid Nazeri used PFC3D to simulate rock movement through an ore pass (Nazeri, Mustoe et al. 2000). His paper chose to compare clustered particles to circular particles and compared these results to that of the mine. It was determined in this paper that stresses were inconsistent with that of circular ore and that material flow tended to "hang up" in ore passes when using clustered particles. Both of

these papers support the use of clustered, conglomerated particles to represent rocks within a system. However, both of these papers used clustered rocks to represent forces and not rock flows. Even Nazeri's paper only found that "hang ups" were more evident when trying to compare flow.

While some research did recommend the use of clustered, agglomerated particles within PFC to represent actual rocks, other research mentioned its unimportance. A paper similar to Nazeri's decided to just use large circles combined with fine, much smaller, circles to show actual hang up and ore flow (Iverson 2003). This paper showed acceptable results using circular particles in PFC2D. S. Masson used PFC2D to compare particle mechanical properties on silo flow, and confirmed the efficiency of PFC for leading numerical analysis of granular flow (Masson and Martinez 1999). Fine particle research also involved single spherical particles. This analysis discovered the flowability of smaller particles representing small glass beads (Moreno-Atanasio, Antony et al. 2005). In each of these cases, circular particles represented flow through a silo successfully.

Other simulations include a large number of particles in attempt to represent an actual silo. D.R. Parisi along with S. Masson (2004) used discrete element method to develop a hopper that housed 20,000 – 170,000 particles. This method actually layered the particles in order to validate the model to actual silo flow. Stresses and velocities were also calculated by the model. By separating the large system of particles into subdomains, the program was able to run a large number of particles. The results of this paper showed a very small discrepancy in the displacement fields. The overall results, however, were very reliable, and once again prove that flow can be measured using spherical particles.

4. Residence Time Distributions

Residence time distributions (RTD's) are the results determined by tracer tests performed on any type of reactor. The purpose of an RTD analysis is to determine the mean residence time, the extent of mixing within the reactor, and to identify unusual operating problems. The recovery of a given component is determined by these conditions. The extent of mixing within the reactor is defined as either plug flow, mixed flow, or arbitrary flow. Plug flow represents a perfect reactor with no mixing; what goes into the reactor leaves the reactor as the same concentration. Mixed flow represents a reactor where mixing is taking place (Levenspiel 1972). Figure 2.3 represents the type of reactors and the associated mixing which takes place with each reactor.

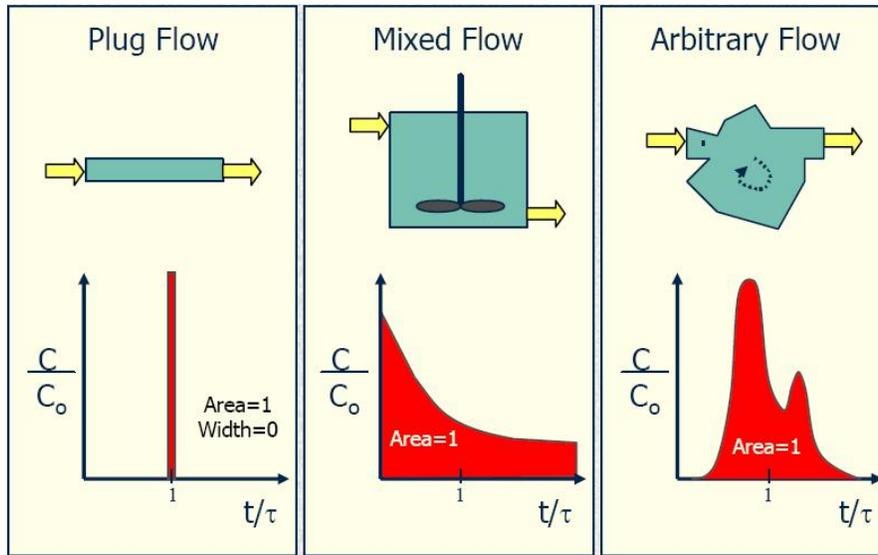


Figure 2.3 - Reactor mixing classifications

A perfectly plugged flow is rare in most reactors. Because of this, reactors are measured by the degree of mixing within the reactor. This mixing variable is defined as the Peclet number, or mixing intensity. The higher the Peclet number, the more plug flow the reactor is. In the case of an aggregate stockpile, it is believed that little mixing occurs within the pile. Therefore, the stockpile is assumed to operate in a plug flow manner. While within the pile, very little mixing is taking place, the introduction of rocks to the pile may cause immediate rock separation, or mixing. This paper proves to verify both cases.

When determining the mean residence time and Peclet number of a stockpile, the following equation is used:

$$\frac{C_t}{C_o} = \frac{1}{2\sqrt{\pi(t/\tau)/Pe}} \exp\left\{-\frac{[1-(t/\tau)]^2}{4(t/\tau)/Pe}\right\}$$

Where, C_t = Species concentration at time t

C_o = Normalizing number (original concentration)

t = Current time

τ = species retention time

Pe = Peclet Number (mixing intensity)

This equation was used to determine RTD of a generic reactor, or system. In the case of a stockpile, a generic reactor was decided upon because there was no real previous knowledge of internal flow. Once concentrations at various times were determined, the residence time and Peclet Number calculated were able to generate an understanding of how particles reacted in the stockpile (Levenspiel 1972).

Chapter 3: Residence Time Distribution Analysis of an Aggregate Stockpile

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Abstract

Much of the stockpile research of today focuses on how to improve efficiencies associated with stockpiles by simply having a better understanding on blending techniques. In many aggregate mines, understanding timing and flow of a pile is just as important for timed sampling and process adjustments. This paper studies the results found from RTD analyses performed on three separate stockpiles. These results proved that within an aggregate stockpile, rocks discharge from a stockpile similar to that of a plug flow system. However, it was also determined that conveyor loading techniques can cause separation of a particular group of rocks prior to discharge. Early separation of rocks lengthened the discharge distribution time, thus leading to a lower Peclet number more representative of a mixed system. Mean residence times found in each analysis were deemed useful for this particular stockpile, but could not be used to represent retention for every aggregate stockpile. It is recommended that future physical flow research perform a larger number of RTD analyses in order to develop discharge rate equations useful for any size and type of aggregate stockpile.

1. Introduction

In the aggregate industry, stockpiling is the primary method of storing rock. Both product and plant rock are stored in stockpiles. Stockpiles are used over other storage methods because of the various required loading techniques and the ability to actually store the rock in this fashion. Silos, and other storage devices, are an unnecessary added cost and are needed only if the material to be stored is toxic, flows freely, or requires a special discharge technique. While stockpile storage of aggregate material is preferred, little is known on particle flow through a stockpile when discharged from beneath the pile. This is essential in obtaining proper samples and in understanding how particles move through a stockpile.

While there is limited research on stockpiles and their internal flow, there is much research involving quality control. Quality control is important in controlling product and throughput for a plant. For example, stockpile performance numbers captured by a quality management program were used to help make proper adjustments as shown in P. Keleher's paper (Keleher, Cameron et al. 1998). J.E. Everett (Everett and Kamperman 2000) discussed how simple adjustments to discharge rates and pickup timing can improve mine life and quality of product. Another example is seen in M.G. Nelson's paper where push piles are used to blend different grades of phosphate by correctly using a real-time analyzer (Nelson and Riddle 2004). These are just a few examples of the research associated with blending and quality control.

Other research is usually associated with displacement of piles and the results associated with displacement. B. A. Quinn (Quinn and Partridge 1995) had an article which more focused on displacement of a stockpile due to fines. He performed lab tests to determine whether excessive fines and lack of medium size particles can cause a decrease in stockpile slope stability. Jenike & Johnson (Carson, Royal et al.) has done research focusing on segregation of stockpiles leading to rat-holing and sifting. Segregation is an issue when loading onto aggregate stockpiles due to the excessive amounts of fines that load near the center of the pile. Also, overall safety and control of how particles enter and leave a pile are better understood with this research.

All of the research available today shows the importance of stockpile management but lacks the understanding of how particles flow within the pile. In addition, there is very little experimental research associated with stockpile flow. Research that could prove the amount of mixing occurring within the pile would allow for better understanding on what to expect during discharge. In the case of aggregates, sampling the discharge of stockpiles is important for quality control and when specific tests are needed to rate performance. Sometimes stockpile adjustments can be very difficult to time and can skew data or cause excessive wait time in order to assure a sample of a specific rock. There are also times where various changes in rock

hardness and size can throw off a plant or cause damage to various parts of a plant. The addition of experimental stockpile flow research would provide a better understanding of the mixing and flow rate occurring within an aggregate stockpile.

Although, much of the research of today shows the importance of stockpile management and control, it lacks important internal flow research that could better explain the movement of rocks within a discharging stockpile. Provided what we know today, a better understanding of how particles react upon discharge of a stockpile would allow for better models and more efficient research. The purpose of this paper is to discuss the results obtained while performing an RTD analysis on an aggregate stockpile. These results will provide a better understanding on the degree of mixing within an aggregate stockpile during discharge. Also, mean residence times of various aggregate stockpiles will be evaluated in hopes of determining a better understanding of average retention times within stockpiles. It is believed these results will assist in understanding the above stated issues while also providing new knowledge on internal flow characteristics of an aggregate stockpile.

2. Analysis of a Stockpile Reactor

In this paper, residence time distribution analyses were performed on many stockpiles. Residence time distributions (RTD's) are the results determined by tracer tests performed on any type of reactor. The purpose of an RTD analysis is to determine the mean residence time, the extent of mixing within the reactor, and to identify unusual operating problems. The recovery of a given system is determined by these conditions. These conditions are important in properly understanding the internal flow and mixing taking place within a stockpile.

Within an aggregate stockpile, three types of mixing are likely to take place: Plug flow, mixed flow, or arbitrary flow. Plug flow represents a perfect reactor with no mixing; what goes into the reactor leaves the reactor as the same concentration. Mixed flow represents a reactor where mixing is taking place (Levenspiel 1972). Figure 3.1 represents the type of reactors and the associated mixing which takes place with each reactor.

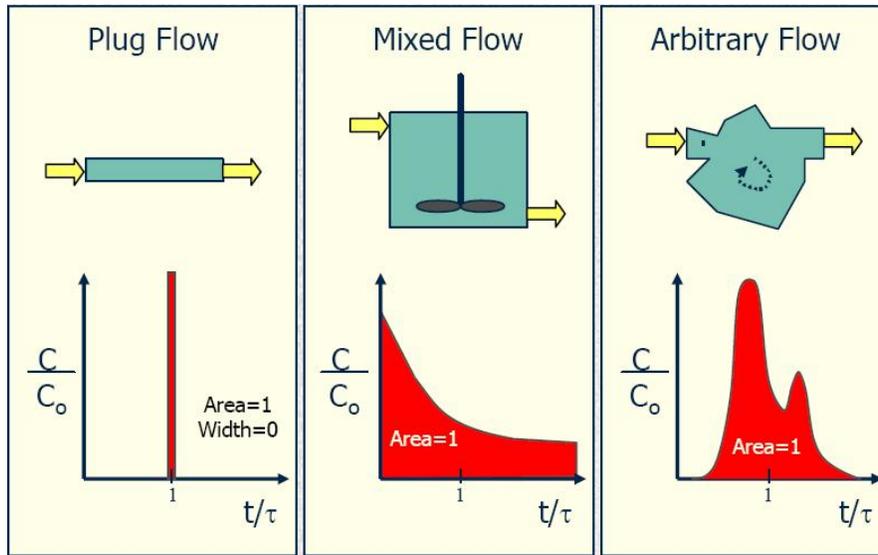


Figure 3.1 - Reactor mixing classifications

A perfectly plugged flow is unlikely to occur within a stockpile. Because of this, the results taken from the stockpile are measured by the degree of mixing within the stockpile. This mixing variable is defined as the Peclet number, or mixing intensity. The higher the Peclet number, the more plug flow the reactor is. In the case of an aggregate stockpile, it is believed mixing occurs differently depending on the location of interest within the stockpile. Therefore, the stockpile is assumed to operate in an inconsistent manner. It is also assumed that the introduction of rocks to the pile may cause immediate rock separation, or mixing. This paper proves to verify both cases.

When determining the mean residence time and Peclet number of a stockpile, the following equation is used:

$$\frac{C_t}{C_o} = \frac{1}{2\sqrt{\pi(t/\tau)/Pe}} \exp\left\{-\frac{[1-(t/\tau)]^2}{4(t/\tau)/Pe}\right\}$$

- Where, C_t = Species concentration at time t
- C_o = Normalizing number (original concentration)
- t = Current time
- τ = species residence time
- Pe = Peclet Number (mixing intensity)

This equation was used to determine the RTD of a generic reactor, or system. In the case of a stockpile, a generic reactor was decided upon because there was no real previous knowledge of internal flow. This equation was combined with concentration results at different time periods in order to determine reliable flow data. This was done by assuming original Peclet number and residence times. The resulting concentration, based on these guesses, was then compared to

the original stockpiles concentration. The Microsoft Excel solver function was then used to adjust mean residence time and Peclet number accordingly until the sum of squares was minimized. These results were then used to describe the flow of the aggregate stockpile.

3. Residence Time Distribution, RTD, Analysis

3.1. Analysis Introduction

An RTD analysis was performed on three aggregate stockpiles over three days. Each stockpile had a different shape and each was discharged at a different flow rate. The first RTD analysis was performed on tracer rocks located at a selected position on the pile. The purpose of this test was to see how the rocks separated during discharge. The next two tests allowed for random introduction of particles by means of conveyor. These tests showed how particles separated when being introduced randomly to the pile and how it may have adjusted the Peclet number. The following procedure describes how each test was set up and completed.

3.2. Analysis Setup Procedure

Correct sampling and analysis procedures were essential in obtaining proper RTD's. There has been little to no RTD analytical work done on stockpiles, so the setup was designed solely on similar tracer tests and reasonable estimations. In order to perform an RTD analysis tracer rocks were to be located in the pile and monitored when leaving the pile. Capturing this information was essential in understanding the mean retention time in the pile and in understanding how rocks perform when flowing through the pile.

3.2.1. Determining a Location

Preparation of stockpile analysis began by first establishing a mine at which to perform the RTD analysis. After much consideration of many aggregate mines, it was decided to focus on Luckstone mines due to previous work experience with the company and the company's understanding on the importance of aggregate research. Because Virginia Tech had previously done research with Luckstone's Bealeton, Virginia, mine for a Mine-to-Mill project, this mine was deemed the best option for the analysis. Also, rocks from a previous test at the mine had been stored at Virginia Tech and could be used for this analysis. Overall, the mine was a perfect fit for the type of project environment needed for a reliable analysis.

3.2.2. Tracer Rock Setup

After choosing the Bealeton mine as the analysis location, the rocks, stored at Virginia Tech's office, had to be sorted through in order to choose a viable tracer rock size class. This was decided based on what size rock would be presented to a crusher and what rock is targeted as product. In order to produce product, larger rocks from the pit must be crushed and sized in order to meet product specifications. Understanding this, the decision was made to use rock sizes larger than the secondary crusher setting but rocks after primary crushing. Rock sizes were limited to large rocks subsequent to primary crushing mainly because these rocks were the first presented into a stockpile at the facility, and were of a reasonable size. Considering Luckstone's operating parameters, it was decided that two size rocks be used as tracers: 3 to 3.5 inch rocks, or "small" rocks, and +6 inch rocks, or "large" rocks. These rocks remained larger than the closed-side setting of the secondary crusher.

Once rocks sizes were decided upon, the quantity of tracer rocks to use in the analysis was then needed. In order to represent the stockpile, enough tracer rocks had to be used so that the results could be deemed reliable. In this case, the number of rocks needed to be chosen so that each could be accounted for when leaving the pile. Most tracers used today tend to be radioactive and are measured based on the radioactive intensity of the exit stream. A stockpile, however, cannot be treated this way considering the size and consistency of the material being studied. Because of this, the amount of tracer rocks needed was decided upon based on predicted results. Estimating that at least 20% of the rocks will be unaccounted for, it was decided that 50 rocks be used as the tracer sample. Each size class (3-3.5 in. and 6+ in.) will consist of 25 rocks and will be located together on the pile. Losing 10 of the 50 rocks will not hurt the analysis enough for the results to be unusable. In fact, 40 rocks were believed to be plenty to determine mean retention time and mixing intensity.

After determining the size classes and quantity of rocks to use in the analysis, a method of tracing the rocks was needed. It was first believed that a small transponder could be located within the rock and the rock could be monitored electronically as it entered and exited the pile. This method was set up and used during the first analysis. Setting up this method consisted of drilling small 0.25 inch holes approximately 1.25 inches deep into each rock. A single transponder was then placed into the hole of each rock followed by a silicon gel application to both protect the transponder and keep it in place. While this approach worked well in a lab setting, problems arose while attempting to track the transponders while in the field. It was believed interference either from the belt idlers or the speed of the belt itself was preventing the transponders from being read by the antennas placed over the product belt. Because there was reason to believe this issue may occur, a backup method was used to trace the rocks as they

exited the pile. In order to distinguish the rocks as they were leaving the pile, a visual spray painting method was set up. Each rock in each size class was spray painted in order to differentiate it from other rocks. The spray painted rocks were noticeably different in color from the standard gray rocks and were now ready for the stockpile analysis. The spray paint applied to each rock allowed for each rock to be traced as they exited the pile, regardless of whether or not the transponders worked correctly. Because of this, transponders were only used during the first analysis; no resulting data collected using the transponder tracing method has been provided within this paper.

3.2.3. Equipment Preparation

Once the tracer rocks were ready for the field analysis, visual and survey equipment was collected for use. The visual equipment consisted of a Sony TRV-900 minidv camera with tripod, which would be used to visually record the outflow of rock from the pile. This camera was the premium 3CCD (charged coupled device) digital camcorder which was capable of monitoring the three primary colors. This camera was chosen because of its technology and its ability to capture colors well. Survey equipment consisted of MDL LaserAce 300, which is a laser surveying system. This system was capable of obtaining distances and angles without the use of a tripod. This would be used to determine the stockpiles height and basic dimensions before discharge.

3.3. On-site Analysis Setup

Over the course of seven months, three separate stockpile analyses were completed at the Luckstone quarry in Bealeton, Virginia. The purpose of the first analysis was to determine how particles separated during discharge when placed at the same location on the pile. The second and third analysis both allowed random introduction of tracer rocks into the stockpile. The ultimate purpose of all three experiments was to determine the degree of mixing within the stockpile while discharging and the mean residence time.

3.3.1. Analysis Setup 1

On October 21, 2005, tracer rocks and analysis equipment were transported to the Luckstone mine in Bealeton, Virginia in preparation for the RTD analysis. Upon arrival at the mine, managers and employees were notified of the work that was going to be done and of the

assistance that may be needed. Once understood, tracers and equipment were prepped for the analysis.

With the assistance of managers and employees, a stockpile was chosen for use in the analysis. It had been previously determined that a primary stockpile would be used, but there were two on site that could be used. A stand alone stockpile separate from the standard primary stockpile was chosen to be the best option. This pile was used because its size was smaller than Luckstones other primary piles and had one drawpoint. The size made it favorable for placing the tracer rocks at a set location on the pile while the single drawpoint made the pile consistent to that of the PFC simulation.

Once the pile was chosen, the tracer rocks were ready to be located on the pile. It was decided that in the first analysis the rocks were to be located together at a central location at the very top of the pile. While the pile was not completely full, there was still a peak at the top of the pile where the tracer rocks could be placed. In order to place the tracer rocks, a manlift hoisted the rocks up to the pile where the rocks could be located safely. Once the rocks were placed on the pile, the manlift was lifted higher so that the stockpile could be surveyed. Figure 3.2 shows placement of the rocks at the peak of the stockpile. Figure 3.3 shows a side view of the pile with the tracer rocks sitting at the top of the pile.



Figure 3.2 - Placement of rocks at peak of stockpile



Figure 3.3 - Side view of pile (tracer rocks located at peak)

3.3.2. Analysis Setup 2 and 3

Analyses 2 and 3 were setup similarly on April 19, 2006 and May 23, 2006 at the Luckstone mine in Bealeton, Virginia. Like the first analysis, the manager and employees were notified of the situation and were prepared to assist in the exercises. Upon arrival at the mine, the same stockpile used in the first analysis was filled to near-full capacity and surveyed.

Unlike the first analysis, these analyses allowed for random introduction of tracer rocks to the pile. This was done by adding the tracer rocks randomly to the conveyor which feeds the stockpile. Once the conveyor was loaded with the tracer rocks, the conveyor was turned on and the rocks were dumped onto the pile. This method best represented how aggregate rocks were presented to a stockpile. Doing this allowed for rocks to react realistically when hitting the pile and allowed for a random tracer rock distribution. Figure 3.4 shows the rocks on the conveyors just before being presented to the pile while Figure 3.5 shows how the rocks reacted after hitting the pile.



Figure 3.4 - Tracer rocks on conveyor for analysis 2 and 3, respectively



Figure 3.5 - Rock distribution after hitting pile for analysis 2 and 3, respectively

3.3.3. Camera setup

After the each of the stockpiles was prepared for analysis, a camera was then setup to record the flow of rocks from the pile. At the base of the pile, 20 yards from the tunnel exit beneath the stockpile, the camera was setup on a tripod and synchronized with time on the plant control system. The stockpile RTD analysis was now ready to begin. Figure 3.6 shows a visual taken from the video camera just after the stockpile feeder was started.



Figure 3.6 - Still visual taken from video

3.4. Stockpile Analysis

The stockpile feeder and conveyor were started once the setup was completed. The camera was also started while employees and helpers were located next to the belt in order to monitor rock flowing on the conveyor. When tracer rocks passed, they were noted and a brief time was recorded. This was carried until the pile was exhausted and the conveyor belt ran empty. When the pile was empty, cumulative times, flow, and tonnage values were recorded.

3.5. Stockpile Analysis 1 Results

Final results show that the stockpile feeders ran for approximately 0.82 hours until the 30.9 foot stockpile was completely exhausted. During this time the total rock discharged averaged 563.4 short tons per hour, tph. This resulted in a total of 462.0 short tons over the course of the analysis. These results were measured by the online control system used to monitor rock flow through the plant.

The study of video analysis results proved that 45 of the 50 rocks were accounted for during the analysis. This 10% error was less than the 20% anticipated before the test began. However, all of the rocks that went unaccounted for were in the “small” size class. This is understandable considering the smaller rocks could have been trapped under larger rocks and visually unable to detect. It was not believed that the lost smaller rocks affected the final results.

Table 3.1 shows a summary of the tracer rocks and the time range that they left the stockpile. Ranges were used to classify when rocks left the pile so that a mean retention time and diffusivity of the pile could be classified. This information was used to develop the model seen in Figure 3.7. This plot represents the short time period where the concentration of rocks leaving the system was high. As mentioned earlier, 5 rocks are not included in the small rock count column due to being unaccounted for.

Table 3.1 - Analysis 1 rock count summary

	Rock Count	
	Large	Small
9:20 - 10:00 min.	6	6
10:00 - 11:00 min.	13	10
11:00 - 12:00 min.	6	2
12:00 - 13:00 min.	0	2

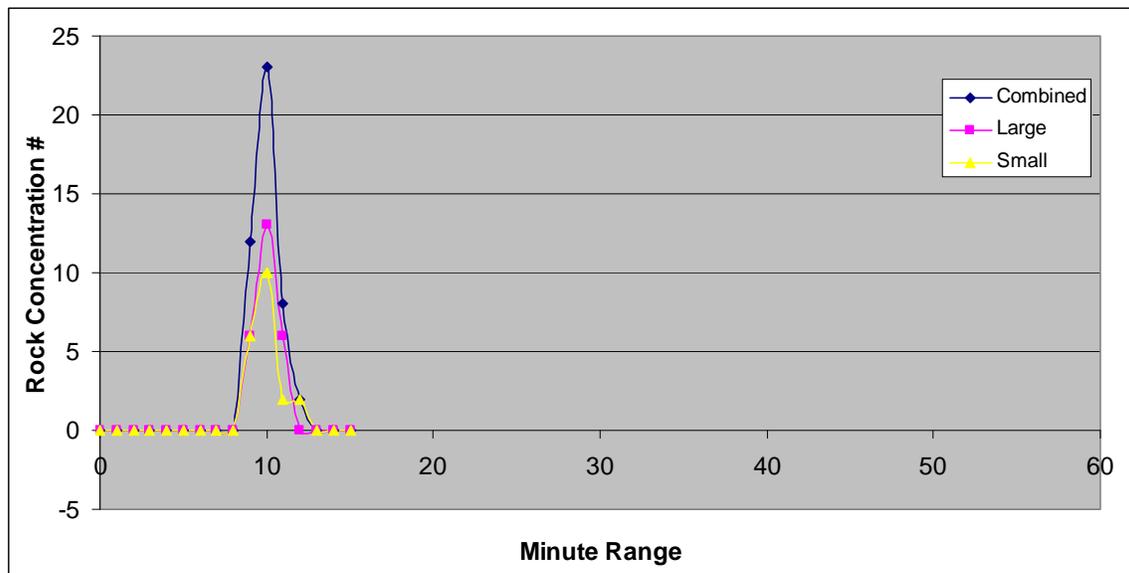


Figure 3.7 - Rock concentration over time for analysis 1

In order to determine the mean retention time and how the flow of the pile was in accordance to where the rocks were located, the following equation was used:

$$\frac{C_t}{C_o} = \frac{1}{2\sqrt{\pi(t/\tau)/Pe}} \exp\left\{-\frac{[1-(t/\tau)]^2}{4(t/\tau)/Pe}\right\}$$

- Where, C_t = Species concentration at time t
- C_o = Normalizing number (original concentration)
- t = Current time
- τ = species retention time, mean residence time
- Pe = Peclet Number (mixing intensity)

The following table created within a Microsoft excel spreadsheet shows the results obtained when solving this equation.

Table 3.2 - Calculated RTD analysis 1 results (time in minutes)

Mean Residence Time	10.37
Peclet Number	371.78
Normalizing Number	4.31
Weighted sum-of-squares	1.85

It was initially noticed that the weighted sum-of-squares was low, proving the equation worked in matching calculated tracer rock concentrations with actual tracer concentrations. The mean retention time was the average time the tracer rocks took to exit the pile once the stockpile feeders were turned on. The mean retention time calculated through solver is accurate.

The Peclet number measures the mixing intensity of a system and is the most important number in understanding particle flow within the system. Peclet number is defined as bulk transport divided by molecular diffusivity. In this case the diffusivity appears to remain very low as the Peclet number was a high 371.78. This means that the stockpile resembled a plug flow during discharge. Meaning, if two of the tracer rocks were located next to one another within the pile, it was likely they exited the pile together, or within a very short time period apart.

3.6. Stockpile Analysis 2 Results

Final results from analysis 2 showed that the stockpile feeders ran for approximately 1.0 hour until the 31.7 foot stockpile was completely exhausted. During this time the discharge rate averaged 405.9 tph., resulting in a total of 414.0 short tons. These results were measured by the online control system used to monitor rock flow through the plant.

The video analysis results proved that 49 of the 50 rocks were accounted for during the analysis. This resulted in a 2% loss which is much lower than the 20% allowable loss decided upon at the start of the analysis. The only lost rock was part of the smaller size class, as was in analysis 1.

The table in Appendix A shows a summary of the tracer rocks and the time range that they left the stockpile for analysis 2. This information was used to develop the model seen in Figure 3.8. This plot represents the concentration of rocks leaving the pile throughout the analysis. As mentioned earlier, 1 rock is missing from the smaller rock size class.

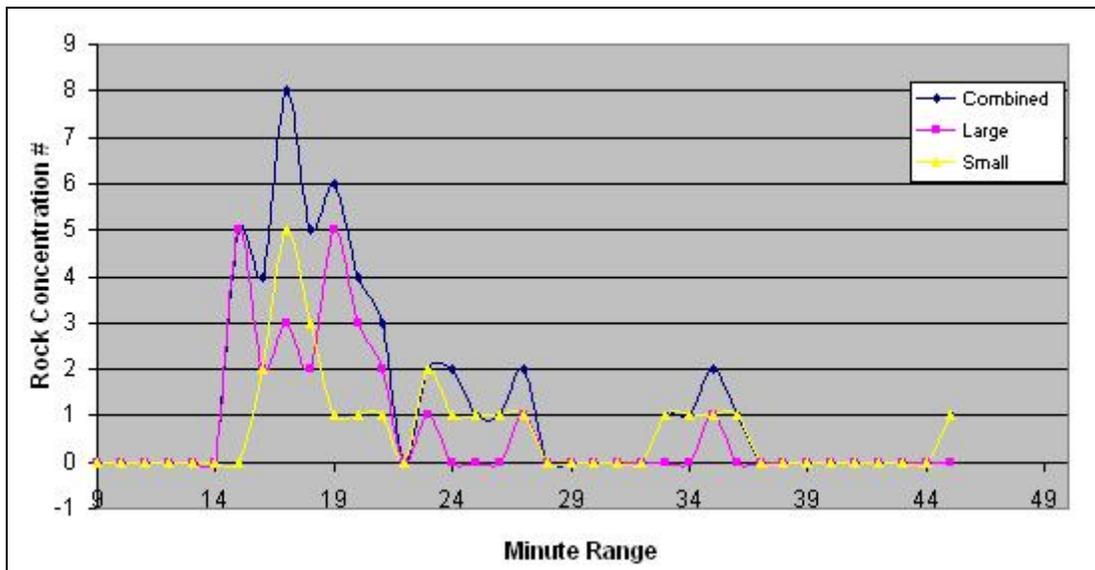


Figure 3.8 - Rock concentration over time for analysis 2

The same procedure that was used to determine the results for analysis 1 was used on analysis 2. The following table shows the results obtained from the data collected during this analysis:

Table 3.3 - Calculated RTD analysis 2 results (time in minutes)

Mean Residence Time	18.25
Peclet Number	112.94
Normalizing Number	2.17
Weighted sum-of-squares	29.79

The weighted sum-of-squares was significantly higher here than what was calculated for analysis 1. This occurred due to the higher number of outlier rocks that discharged later into the analysis. The Peclet number also dropped in analysis 2 because of the larger time range at which the tracer rocks left the pile. The majority of the tracer rocks discharged the stockpile in analysis 1 between the 9:20 to 12:00 minute range. Analysis 2 showed that conveyor method of introducing the tracer rocks to the pile caused an immediate separation in random directions. The majority of the tracer rocks in analysis 2 discharged between 14:00 to 24:00 minutes, as seen in Figure 3.8. The larger time range proved that the system in its entirety, conveyor loading method included, has some mixing during the loading and unloading process. However, the results do show that the majority of the rocks were grouped to a single range.

The mean residence time in this analysis was also higher than that of analysis one. This was expected due to the significant decrease in discharge flow rate during the second analysis.

The introduction of the tracer rocks to the stockpile, however, was not believed to have contributed to the increase of the mean residence time. The increased time range at which the tracer rocks left the pile did expand, but the average did not change because of this.

3.7. Stockpile Analysis 3 Results

Final results from analysis 3 showed that the stockpile feeders ran for approximately 1.25 hours until the 32.5 ft. stockpile was completely exhausted. During this time the discharge rate averaged 369.6 tph, resulting in a total short tonnage of 462. These results were measured by the online control system used to monitor rock flow through the plant.

The video analysis results proved that 48 of the 50 rocks were accounted for during the analysis. This resulted in a 4% loss which is, once again, much lower than the 20% allowable loss decided upon at the start of the analysis. As with analysis 1 and 2, the only tracer rocks that went unaccounted for were part of the “smaller” size category.

The table in Appendix A shows a summary of the tracer rocks and the time range that they left the stockpile for analysis 3. This information was used to develop the model seen in Figure 3.9. This plot represents the concentration of rocks leaving the pile throughout the analysis. As mentioned earlier, two rocks were unaccounted for from the smaller rock size class.

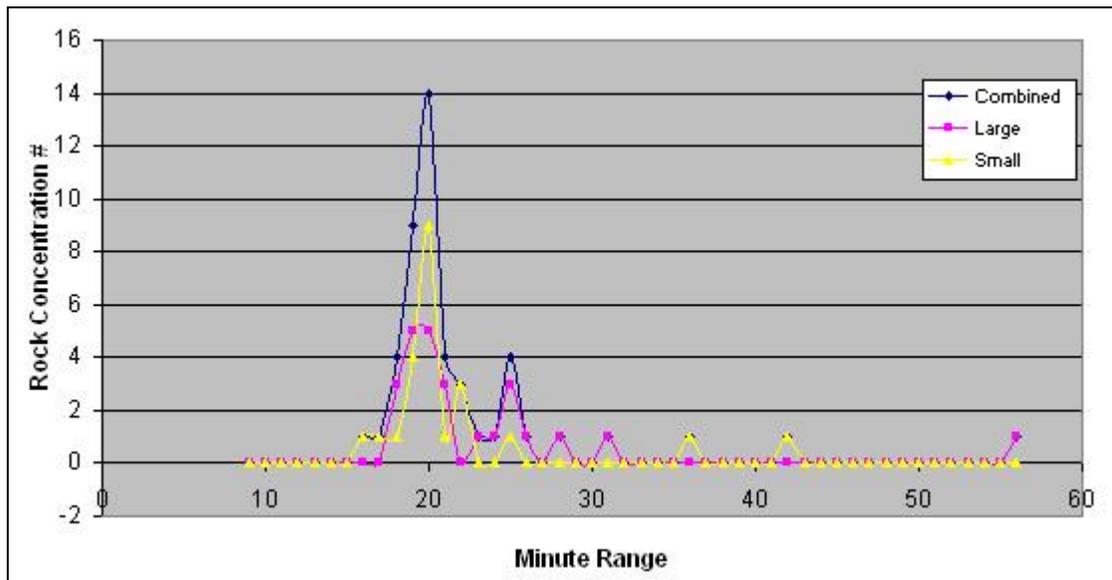


Figure 3.9 - Rock concentration over time for analysis 3

The same procedure used to determine the results for analyses 1 and 2 was completed on analysis 3. The following table shows the results obtained from the data collected during this analysis:

Table 3.4 - Calculated RTD analysis 3 results (time in minutes)

Mean Residence Time	20.20
Peclet Number	793.30
Normalizing Number	1.64
Weighted sum-of-squares	37.41

As with analysis 2, the weighted sum-of-squares was significantly higher for analysis 3 than what was calculated for analysis 1. Once again, this occurred due to the higher number of outlier rocks that discharged later into the analysis. In this particular case, there were more outliers that sat farther away from the primary discharge range between 18 and 22 minutes. Because of this, the sum-of-squares was even higher than that of analysis 2.

Unlike analysis 2, the Peclet number actually increased higher than that of analysis 1. This higher Peclet number, which represented a more plugged flow, was understandable given the results of the analysis. Analysis 3 had a higher peak discharge period closer to 20 minutes as compared to 10 minutes in analysis 1. Figure 3.9 also shows how the plot resembles that of analysis 1 rather than analysis 2. This basically means that the tracer rocks had to remain closer together throughout the loading and unloading period for a longer period of time. In analysis 2, it appeared that the particles separated more during loading, leading to a more dispersed rock concentration plot. In analysis 3, the particles didn't separate as much upon loading onto the stockpile, with the exception of a few that rolled closer to the bottom of the pile and became outliers. This resulted in a lower discharge rate range and a concentration plot similar to that of analysis 1.

The mean residence time in this analysis was also higher than that of analyses 1 and 2. This was expected due to the even lower discharge rate and increased stockpile size. To further explain what was stated above, the higher mean residence time along with the lower discharge rate range contributed to the high Peclet number.

4. Summary of Results

The results compiled from each of the separate RTD analyses proved different rock flows and reactions during discharge. The first of the three analyses was completed in order to see how rocks located tightly together would flow through an aggregate stockpile. The visual results seen in Figure 3.7 along with a high Peclet number prove that tracer rocks located in a group at the top of a stockpile tend to discharge in a plug flow manner.

Analysis 2 was completed in order to gain a better understanding on how rock introduction to the stockpile affected particle separation. When the tracer rocks were introduced to the stockpile by means of conveyor, it appeared that separation did occur as a few of the larger tracer rocks traveled down the pile (Figure 3.5). This form of separation resulted in a lower Peclet number, or a more mixed system. As observed, the mixing was mainly due to the separation of particles while being introduced to the pile and not due to the discharging of the stockpile.

Analysis 3 was completed similarly to analysis 2. The purpose of this analysis was mainly to validate the results collected from analysis 2. Like analysis 2, the tracer rocks appeared to separate when introduced to the stockpile by means of conveyor (Figure 3.5). However, the Peclet number in this case increased significantly compared to both analyses 1 and 2. Figure 3.9 shows a much “tighter” range where the majority of the tracer rocks discharged. The few rocks that did roll down the pile while loading had little effect on the RTD analysis, and could be considered outliers.

5. Conclusions

Based on the results compiled from the Stockpile RTD analyses performed at Luckstone's Bealeton, VA mine, many conclusions can be made. Analysis 1 proved that tracer rocks located together at the top of the pile tend to travel through the pile and discharge together as a plug flow. While this is true for rocks located at the top of the pile, or within the range directly above the feeder, it may not be necessarily true for particles located at other locations on the pile. It also appeared in analysis 1 that the rocks located directly over the feeder tended to travel faster through the pile. This was noticed when the mean residence time calculated to be just over 10 minutes. With an entire operating time of 54 minutes, this means that the rocks located centrally at the top of the pile discharged within 1/5 of the total discharge time.

Analyses 2 and 3 proved that separation does occur during the conveyor loading process. Even though analysis 3 showed results similar to that of a plug flow stockpile, the process was still considered somewhat mixed because of the visual separation during loading. However, as mentioned earlier, analysis 2 had more of a visual separation upon loading to the pile. Other than this difference, the pile shape and total quantity of rock to be discharged from each pile were very similar. With this being understood, the rocks behavior when being loaded to the stockpile can be deemed arbitrary or immeasurable using the type of tests performed on these analyses. In order to better track overall rock displacement during the loading of the pile, many more sample rocks would be needed.

Overall, it was determined that the aggregate stockpile discharges similar to that of a plug flow system. The introduction of rocks to the pile more influences a mixing of the pile than the discharge of the rocks from the pile. While mean residence times were useful in understanding the general residence time within each pile, they were not very useful in generating an overall understanding of retention within the stockpile. It should be suggested that future physical flow research perform a larger number of RTD analyses in order to develop a correlation between loading and discharge features. In addition, future research should perform residence time distribution analyses on various different starting locations on the pile. This could lead to the development of rate equations based on stockpile height, or volume. Future research may also want to prove how rocks located within the area directly above the discharge point tend to be dominant and travel faster through the pile.

Chapter 4: Simulation and Analysis of Flow Through an Aggregate Stockpile using PFC3D.

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Abstract

In many aggregate mines, understanding timing and flow of a stockpile is important for timed sampling, process adjustments and overall stockpile safety. By developing a model that could simulate particle flow through a pile it would be possible to address these issues in order to reduce down time. This paper represents a simulation of aggregate sized particles through a stockpile using circular particles in PFC3D. Results from the simulation show PFC3D was capable of showing how stockpile particles move in all three dimensions while monitoring specific particles within the pile. These specific particle results provided visual representation on how particles located directly above feeder exit points tend to travel faster through a discharging stockpile. Velocity graphs also showed how particles nearing the discharge point accelerated in the direction of the discharge point before exiting the pile. In addition, the velocity graphs contained evidence leading to the belief that bridging or “arching” could be represented using a PFC3d simulation. While all results provided a better understanding in how particles travel through a discharging stockpile, future testing is recommended. These future simulations should include particles more accurately shaped along with a discharge point which operates similar to that of an actual stockpile discharge feeder. Combining more detailed simulations with more accurate results obtained from further RTD analyses should provide a better representative look on actual stockpile flow.

1. Introduction

In the aggregate industry, stockpiling is the primary method of storing rock. Both product and plant rock are stored in stockpiles. Stockpiles are used over other storage methods because of the various required loading techniques and the ability to actually store the rock in this fashion. Silos, and other storage devices, are an unnecessary added cost and are needed only if the material to be stored is toxic, flows freely, or requires a special discharge technique. While stockpile storage of aggregate material is preferred, little is known on particle flow through a stockpile when drawn from beneath the pile. This is essential in obtaining proper samples and in understanding how particles move through a stockpile.

While there is limited research on stockpiles and their internal flow, there is much research involving quality control. Quality control is important in controlling product and throughput for a plant. For example, stockpile performance numbers captured by a quality management program were used to help make proper adjustments as shown in P. Keleher's paper (Keleher, Cameron et al. 1998). J.E. Everett (Everett and Kamperman 2000) discussed how simple adjustments to discharge rates and pickup timing can improve mine life and quality of product. Another example is seen in M.G. Nelson's paper where push piles are used to blend different grades of phosphate by correctly using a real-time analyzer (Nelson and Riddle 2004). These are just a few examples of the research associated with blending and quality control.

Other research is usually associated with displacement of piles and the results associated with displacement. B. A. Quinn (Quinn and Partridge 1995) had an article which more focused on displacement of a stockpile due to fines. He performed lab tests to determine whether excessive fines and lack of medium size particles can cause a decrease in stockpile slope stability. Jenike & Johnson (Carson, Royal et al.) has done research focusing on segregation of stockpiles leading to rat-holing and sifting. Segregation is an issue when loading onto aggregate stockpiles due to the excessive amounts of fines that load near the center of the pile. Also, overall safety and control of how particles enter and leave a pile are better understood with this research.

All of the research available today shows the importance of stockpile management but lacks the understanding of how particles flow within the pile. In addition, there is very little experimental research associated with stockpile flow. Research that could prove the amount of mixing occurring within the pile would allow for better understanding on what to expect during discharge. In the case of aggregates, sampling the discharge of stockpiles is important for quality control and when specific tests are needed to rate performance. Sometimes stockpile adjustments can be very difficult to time and can skew data or cause excessive wait time in order to assure a sample of a specific rock. There are also times where various changes in rock

hardness and size can affect a plant's efficiency or cause damage to various parts of a plant. The addition of experimental stockpile flow research would provide a better understanding of the mixing and flow rate occurring within an aggregate stockpile.

Provided what we know today, a better understanding of how particles react upon discharge of a stockpile would allow for better models and more efficient research. The purpose of this paper is to discuss the results obtained from various particle flow code simulations. These simulations will be used to show how particles flow through a stockpile and how velocities vary within an aggregate stockpile during discharge. The results will also be compared with results obtained from past experimental research in order to validate the model. The results will open the door to future stockpile research and hopefully lead to simulations capable of predicting flow through a stockpile.

2. Simulation of an Aggregate Stockpile

The simulation program that was used to model the flow of rock through an aggregate stockpile was Particle Flow Code in Three Dimensions (PFC3D). The following section describes how the program operates while also providing past research which used the program. Past research was used as a basis for what type of particle flow program to use while also assisting with how to design within the program.

2.1. Particle Flow Code (PFC)

The numerical "Particle Flow Code," or PFC, models sphere particle movement and interaction using the discrete element method. PFC can operate in either 2D or 3D. Calculations in PFC are taken over a series of time steps. This makes it easy on the computer memory in that dynamic equations are performed on every time step, rather than saving and reusing matrices as in an implicit scheme. However, many thousand time steps are run, and calculations are done on each particle for each step. Considering each step is usually a fraction of a second, the program run time is rather lengthy. This can be an issue considering many applications require a large amount of particles to properly simulate a system (L. Lorig, 1995; Itasca, 1995).

There are many papers that have used PFC in a similar manner as is used in this exercise. Hamid Nazeri (2000) used PFC3D to simulate rock movement through an ore pass. His paper chose to compare clustered particles to circular particles and compared these results to that of the mine. It was determined in this paper that stresses were inconsistent with that of circular ore. A similar paper followed the same premise of simulating rock in an ore pass using PFC2D (S.R.

Iverson, 2003). However, their decision to just use large circles combined with fine, much smaller, circles showed results that are acceptable to actual hang up and ore flow. Similarly, S. Masson (1999) used PFC2D to compare particle mechanical properties on silo flow, and confirmed the efficiency of PFC for leading numerical analysis of granular flow. While all of these papers modeled flow through a silo, they proved particle movement can be simulated using PFC.

In every paper that used PFC to simulate particle movement, a similar conclusion was determined. In order to properly see the reactions taking place and the correct movement of the particles, PFC3D should be used. PFC3D was, in all applications, determined to provide a better understanding of the actual rock movement and stress distribution.

2.2. PFC3D Simulation Design

2.2.1. Simulation Introduction

The purpose of this model is to simulate gravity flow in 3 dimensions using PFC3D. Simulating discharge of randomly sized spheres using PFC3D will show the time intervals for different particles in a pile and the movement of the particles at various locations in the pile. This will provide a better understanding on timing and movement of rocks in a stockpile. While many papers suggested grouping particles, clustered rocks will not be used in this exercise deeming simple particle flow through a stockpile can be understood using a simpler, computationally friendly, spherical particle. All code used in preparing and operating each analysis can be see in Appendix B.

2.2.2. Draw Points

Many Stockpiles in today's industry, that require particle to be taken from the pile, have multiple draw points. For this simulation a single draw point was used to calculate retention timing in a stockpile. This was done as a benchmark to see how PFC would respond and map particle flow through a pile. L. Lorig also stated in his paper that a single drawpoint simulation is the simplest to perform.

2.2.3. Wall Development

While the stockpiles used as simulations in this exercise will mimic that of an aggregate mine, the results hope to prove movement of rock through any type of stockpile can be simulated using PFC. For this exercise, conical stockpile shells with heights of 10, 12 and 14 meters were first developed in PFC that had angles of repose of 40 degrees for each cone, respectively. A 40 degree angle of repose was considered an acceptable stockpile shape when at full capacity (J. May, 1991). A floor was then made to act as the ground using 4 individually created walls for each conical shell design. Each of the 4 walls was placed so that a 2 meter x 2 meter or 2.5 meter x 2.5 meter opening was directly centered beneath the cone. Both of the openings were simulated for each conical stockpile shell, resulting in 6 total analyses. Multiple stockpiles sizes and discharge openings were evaluated in order to verify results. Each stockpile discharge was covered to prevent particles from exiting the simulated pile early. All edges that met with other edges were expanded half a meter to prevent leakage. A containment bin was then developed below the cone to contain particles that will be exiting the pile later. Figure 4.1 shows the layout of one of the conical particle containment units with capturing bin.

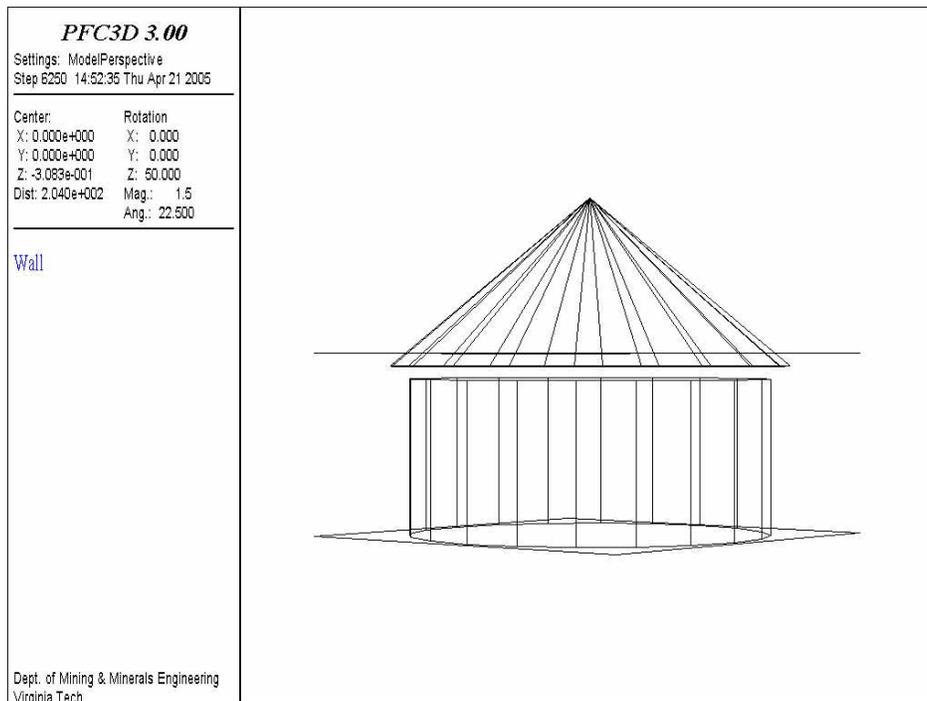


Figure 4.1 - Stockpile shell and capturing bin before particle loading.

2.2.4. Particle Design and Insertion

The particles used in this exercise were decided upon based on actual aggregate rock sizes. A sample taken from the primary stockpile at Luckstone's Bealeton quarry showed rocks ranging from ultra-fine particles to boulders up to a foot in diameter. Because of the size of the cone and the time required to run the program, particles ranged from 0.1 to 0.2 meters. While this eliminated fines completely, it did represent the majority of the particles contained in an actual aggregate primary stockpile. Plus, because the program tended to "freeze up" when trying to use smaller particles, these particle sizes were decided upon.

Locating the particles properly into the cone required a code to fit as many particles as possible. The code did this by filling in gaps with correctly sized particles until a set porosity was met. In this case, an initial porosity of 40% was used due to computer limitations which arose during lower porosity fill periods. While actual porosity numbers should be around 20% (Masson, 1999), the initial 8,000 cycles were ran with the discharge area plugged in order to decrease the porous space between the placed particles. Once particles had been located into a general area at a set porosity, particles that were not located in the cone were removed. This code resulted in a total quantity over 100,000 particles for each of the conical stockpile sizes. Figure 4.2 presents an example of one of the modeled stockpiles as it appeared before simulation.

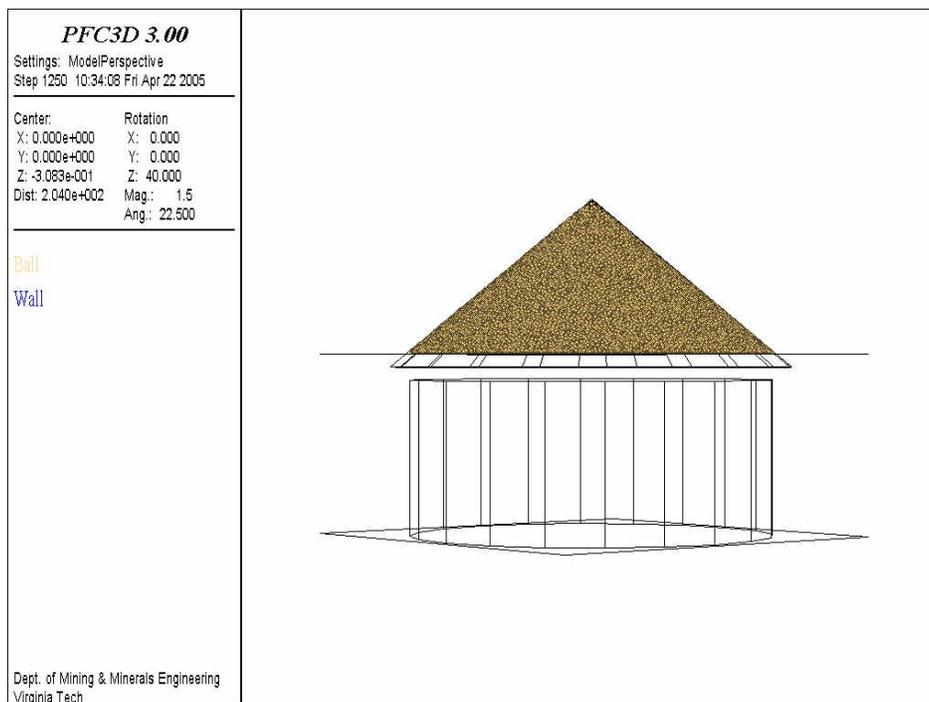


Figure 4.2 - Stockpile loaded with particles before simulation.

2.2.5. Simulation Parameters

Parameters similar to those of actual conditions were used in the simulation of a stockpile. The gravity was set to 9.81 m/s, which is consistent with earth's gravity at ground level. The wall's normal stiffness was set high while its shear stiffness was set to zero considering no friction between the walls and the particles is necessary. The particles were set to have a normal stiffness of $1.0E^6$ N/m, a shear stiffness of $0.5E^6$ N/m, and a friction coefficient of 0.4. While these values were not determined for the particular aggregate rock being modeled, S. Masson used similar values in his studies of rock flow through a silo. Rock in this case should be consistent with the rock used in Masson's paper.

2.2.6. Particle Histories

In order to know how a particle was moving through the stockpile during the simulation, histories were kept for specified particles. These particles were selected based on location and their importance to show the movement of the pile during discharge. While every particle can have a history kept, only a select number of particles were selected. For stockpiles 10, 12 and 14 a total of 40, 45, and 49 particles, respectively, were monitored and had histories maintained during each simulation. An even number of particles were monitored on each respective x and y axis while a single particle was monitored at the top of the pile. Figure 4.3 shows the general location of the particles in the pile that were monitored along the x-axis. The y-axis monitored an identical particle distribution. The points in the figure represent the particles monitored for the 12 meter high conical stockpile design.

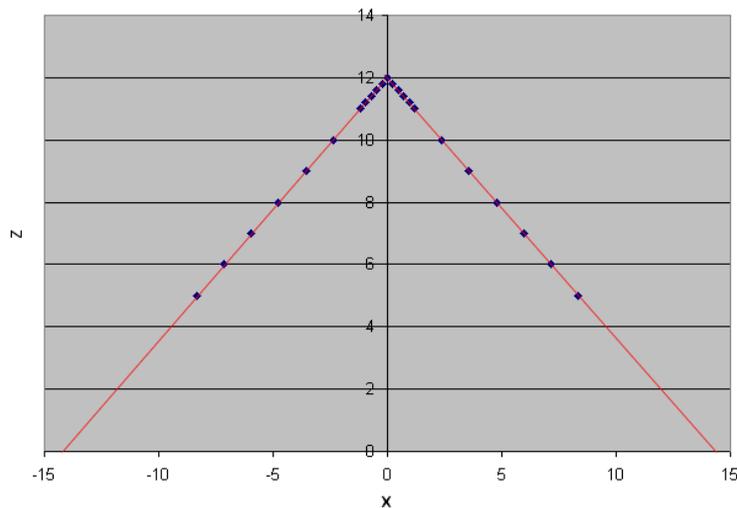


Figure 4.3 - Monitored particle locations for the 12 meter stockpile analysis

2.3. PFC3D Simulation and Analysis

Simulation began by setting up the cone and positioning the particles in the cone. The full simulation was then run through 55,000 cycles, saving the results of the cycles throughout the process. Thousands more cycles were then run until all of the selected particles had moved through the cone. After every 50,000 cycle steps, images and results were saved to monitor particle movement. Appendix B contains all code for each stockpile PFC simulation. Figures 4.4 and 4.5 are images of flow at the start and near the end of simulation for one of stockpile simulations, respectively.

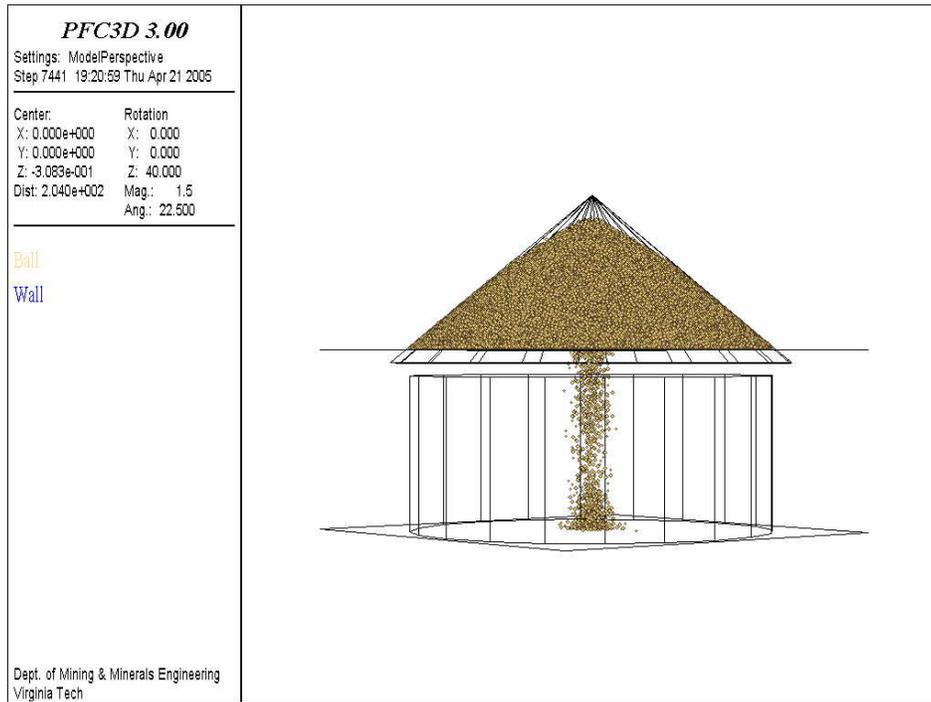


Figure 4.4 - Image after start of simulation.

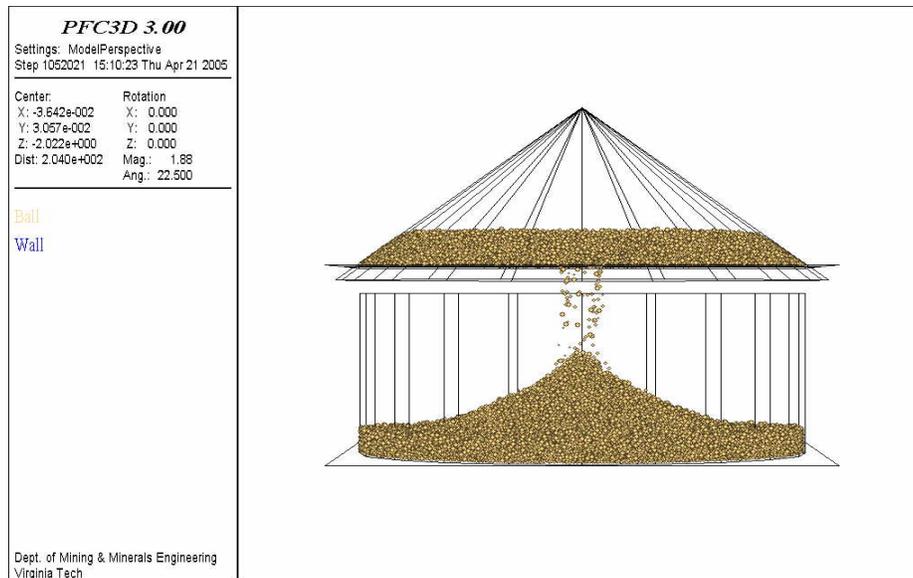


Figure 4.5 - Image near end of simulation.

Figures 4.4 and 4.5 both show the effect of a pile as particles are being discharged. Figure 4.4 shows the immediate effect at the top section of the pile. It appears that the particles closest to the center of the pile are impacted immediately. Figure 4.5 shows that PFC is capable of developing its own random stockpile, as seen with the discharged particles. In this case, it appears that the original stockpile may have had a larger slope stability angle than what should have been used. Comparing both figures, Figure 4.4 shows the heavy discharge of particles while Figure 4.5 shows the slower discharge rate. In operation, the pile is usually recharged while being discharged to keep a constant discharge flow. Considering that in the final figure the majority of the particles had already passed through the discharge point, a lower flow volume was expected.

2.3.1. Particle Displacement During Simulation

After over 1,500,000 time steps had been completed the history files were then inserted into a spreadsheet to locate and monitor how the particles moved through the pile. X-Z and Y-Z displacement graphs were developed to show the total particle flow through the pile. The following figures show the particle locations of each of the particles of which histories were retained for each of the stockpile simulations. These figures represent where the particles started in the pile along with their movement through the pile during the simulations. A total of four Figures are displayed for each stockpile size and discharge type; Two Figures representing the path each particle traveled on the each axis (x and y axis) until the first particle passes through the discharge point and two images representing the path each particle traveled on each axis during the total simulation.

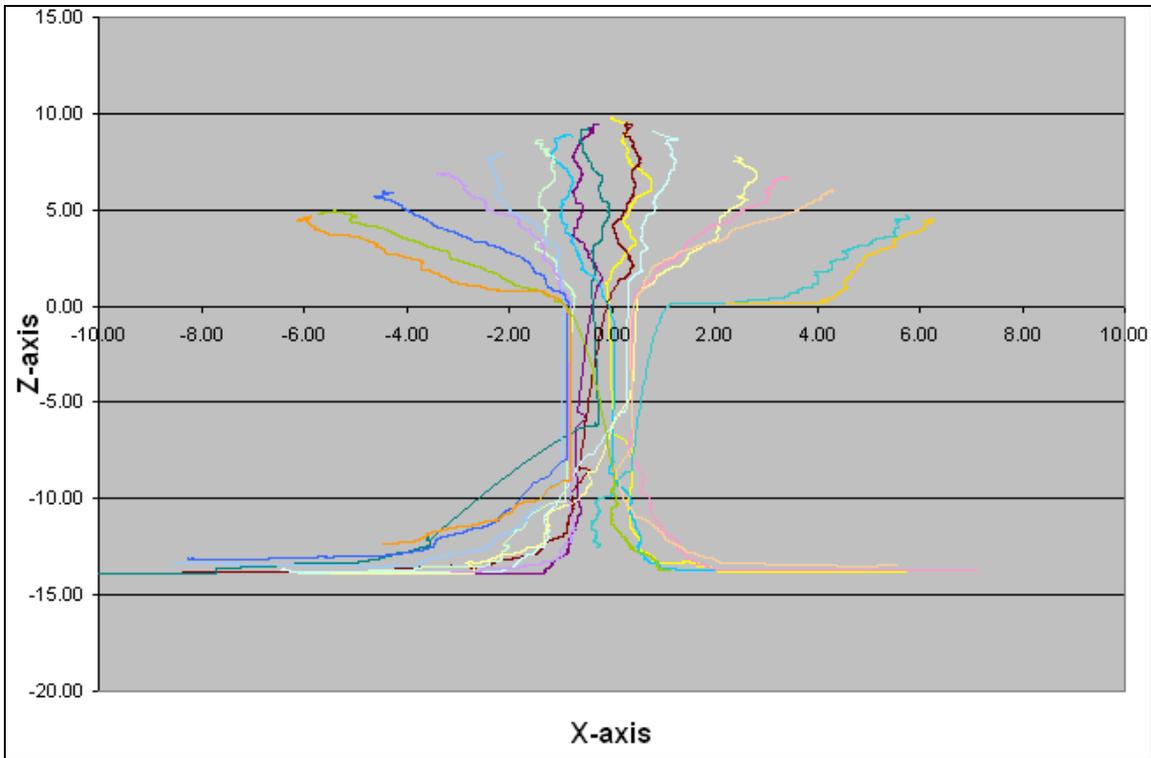


Figure 4.6 - X-Z particle displacement
10 m. stockpile / 2.0 m. discharge

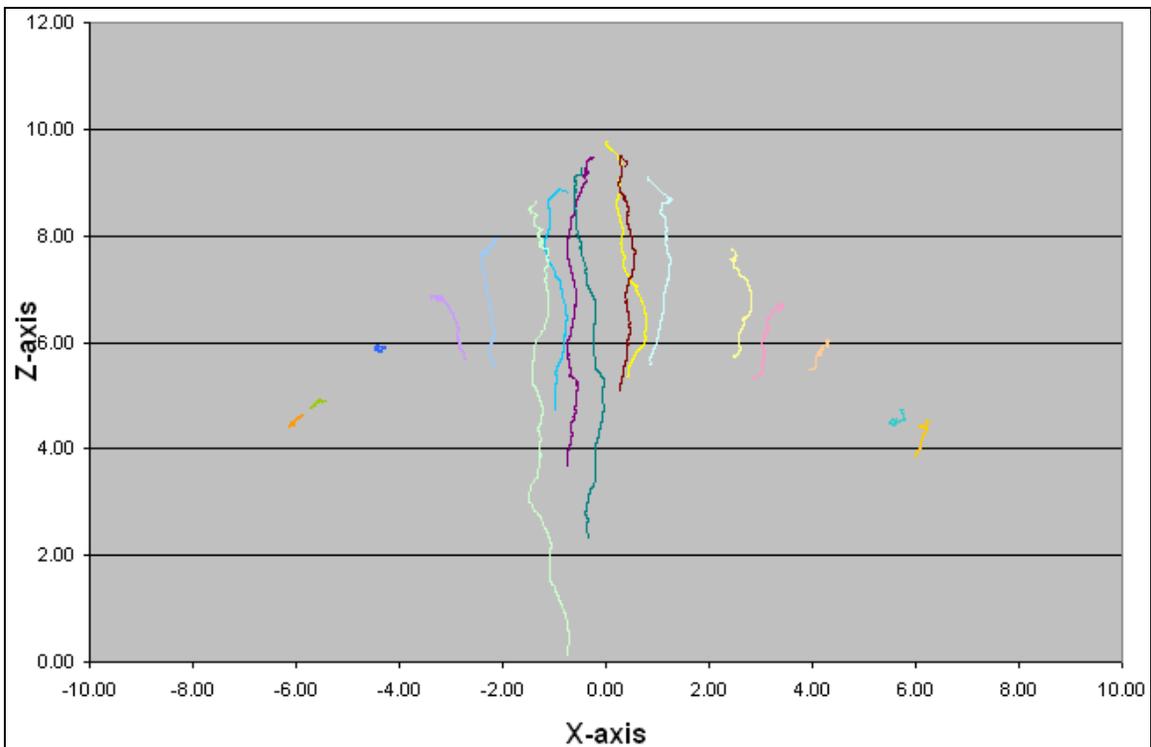


Figure 4.7 - X-Z particle displacement at discharge
10 m. stockpile / 2.0 m. discharge

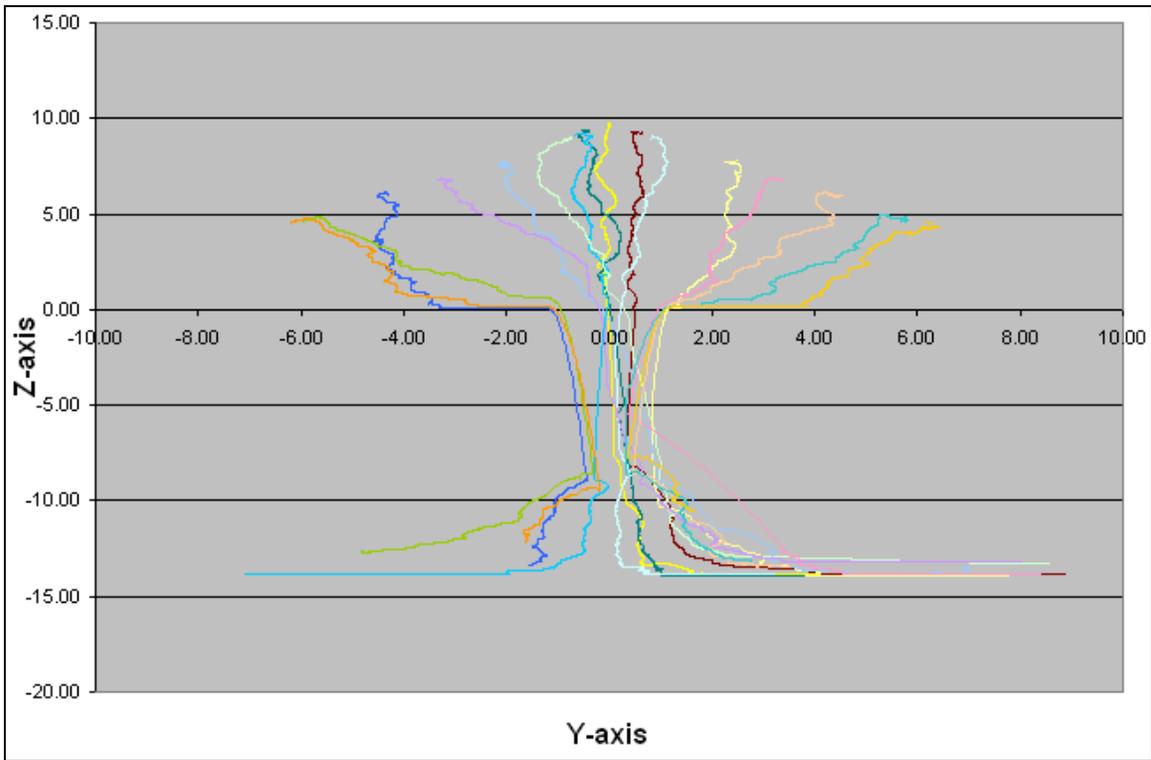


Figure 4.8 - Y-Z particle displacement
10 m. stockpile / 2.0 m. discharge

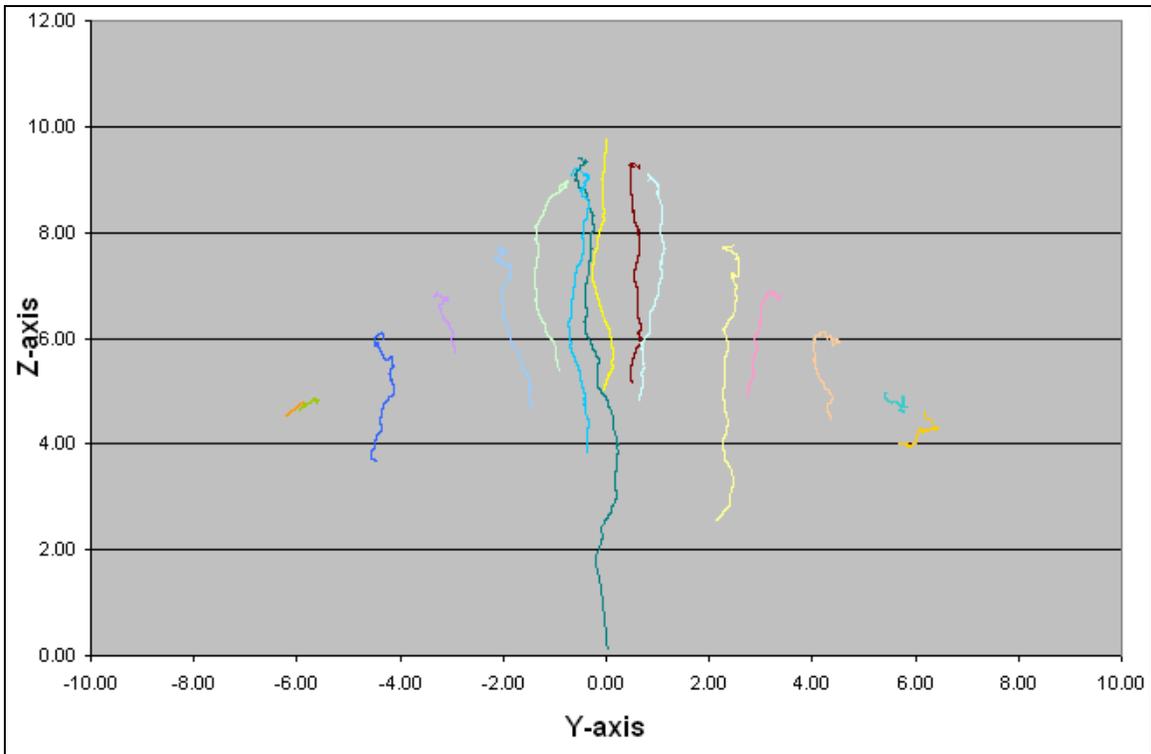


Figure 4.9 - Y-Z particle displacement at discharge
10 m. stockpile / 2.0 m. discharge

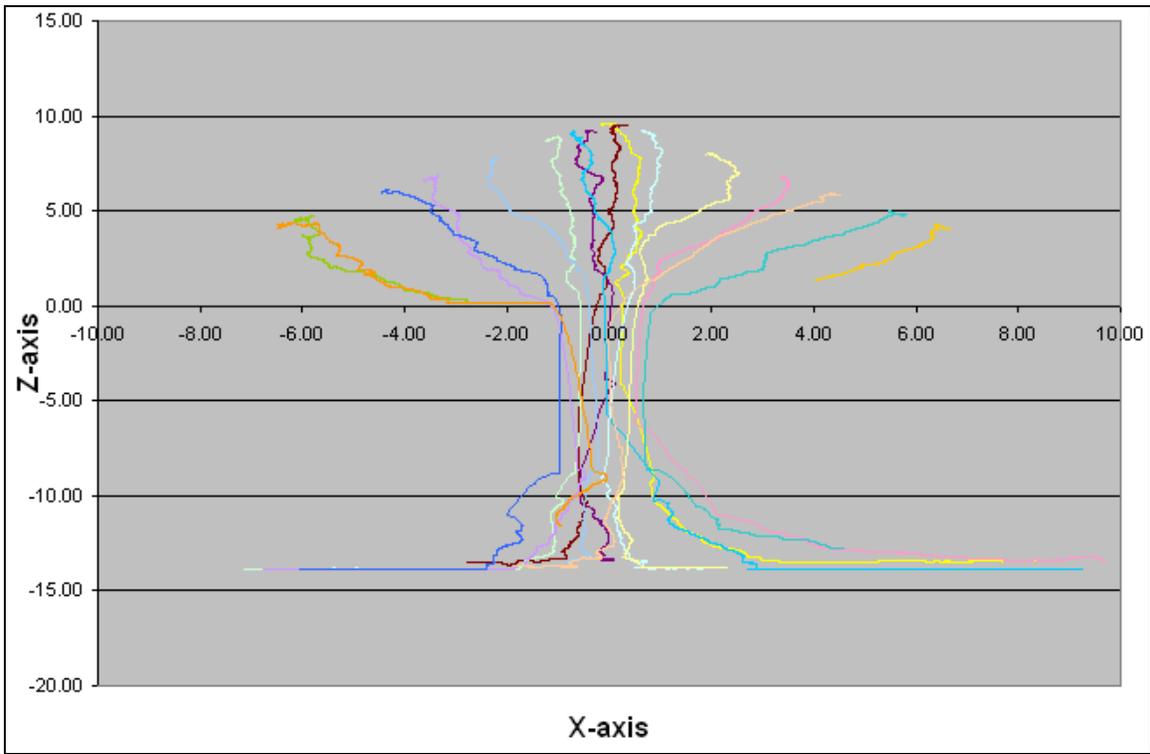


Figure 4.10 - X-Z particle displacement
10 m. stockpile / 2.5 m. discharge

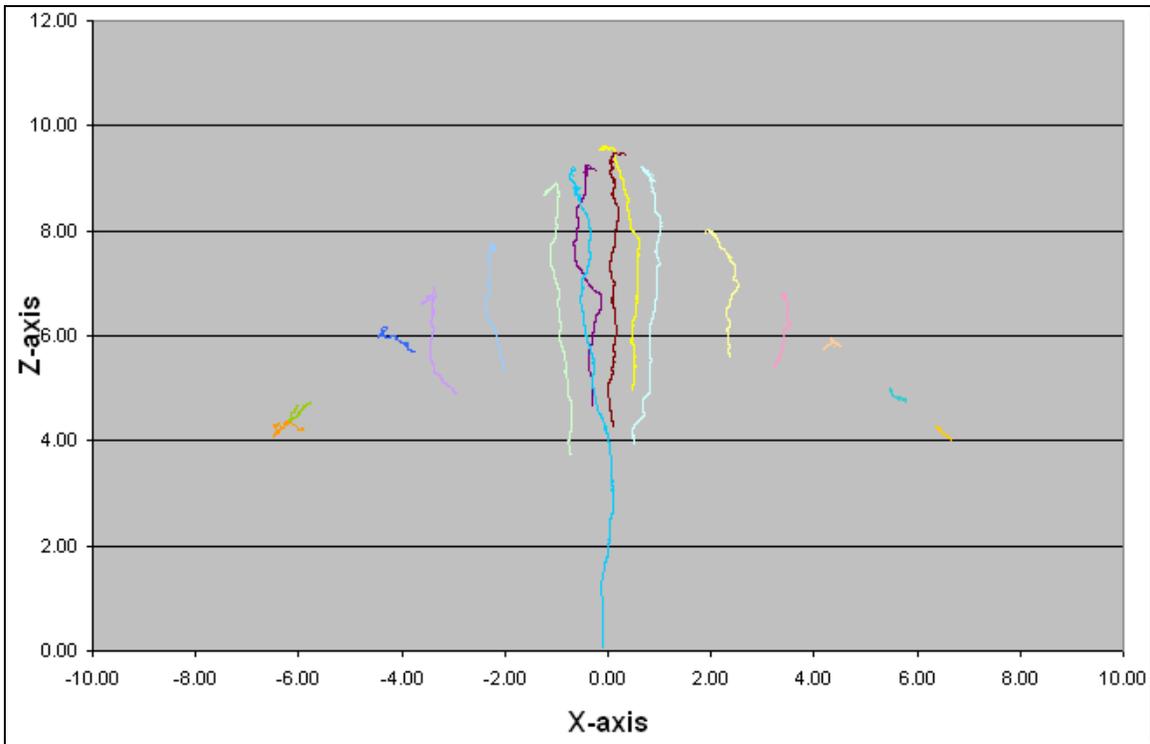


Figure 4.11 - X-Z particle displacement at discharge
10 m. stockpile / 2.5 m. discharge

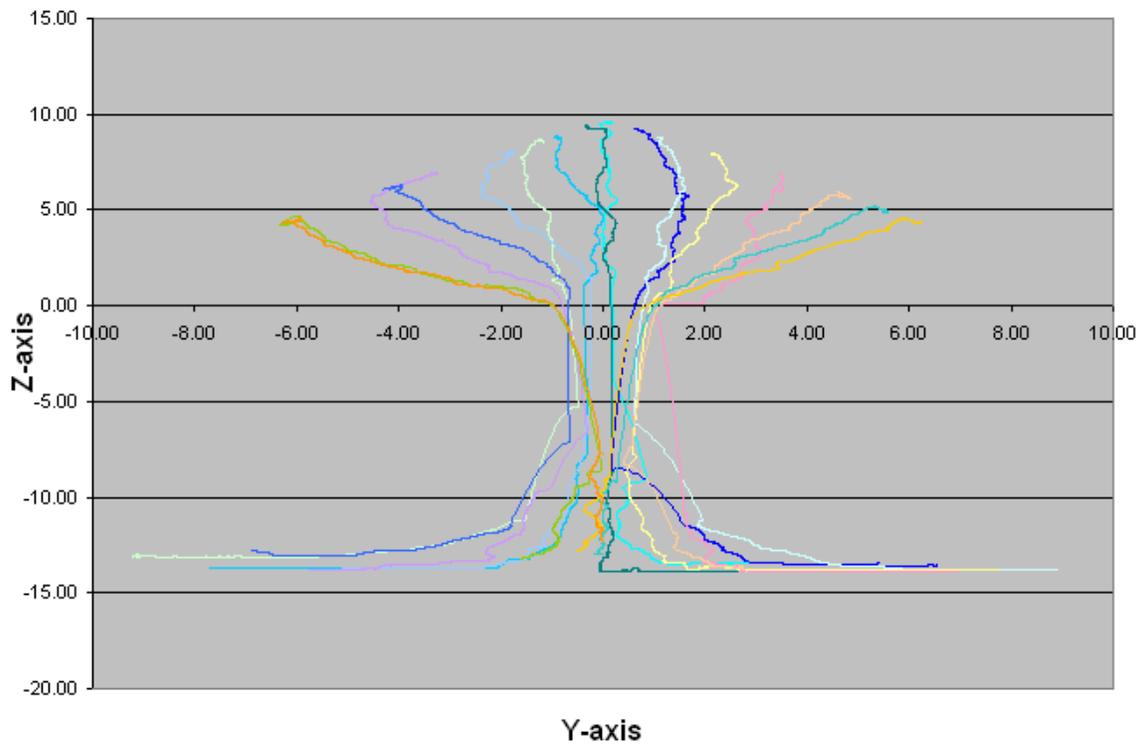


Figure 4.12 - Y-Z particle displacement
10 m. stockpile / 2.5 m. discharge

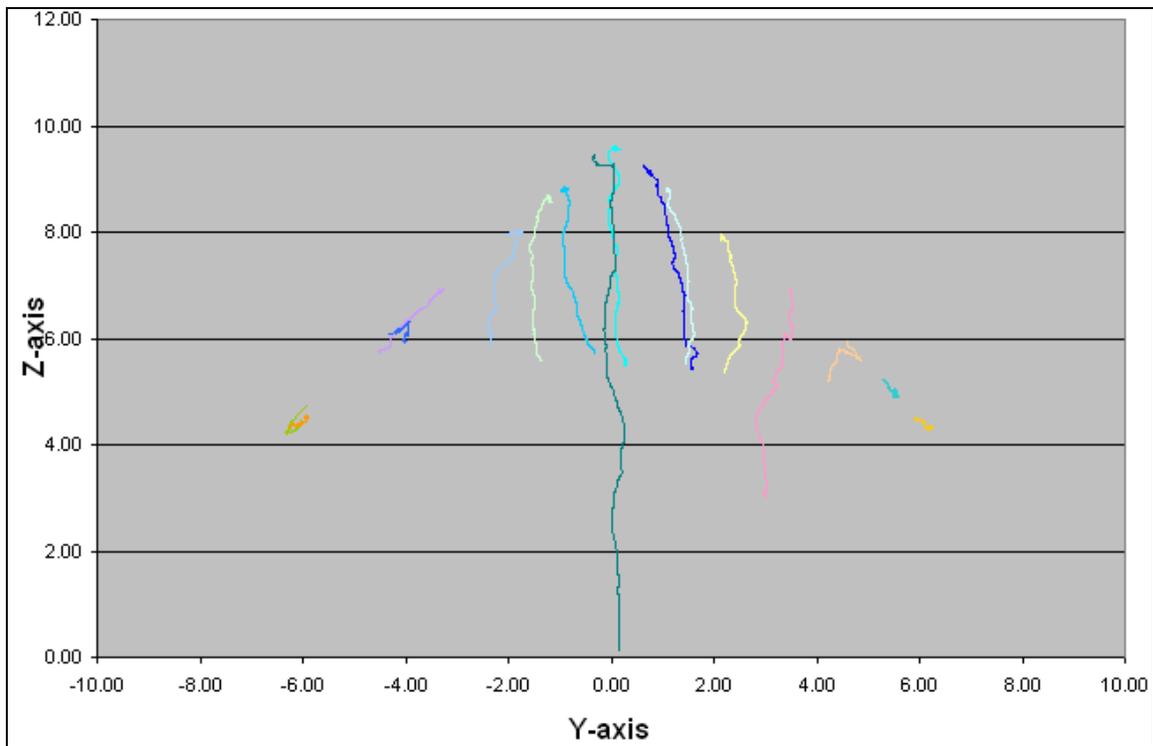


Figure 4.13 - Y-Z particle displacement at discharge
10 m. stockpile / 2.5 m. discharge

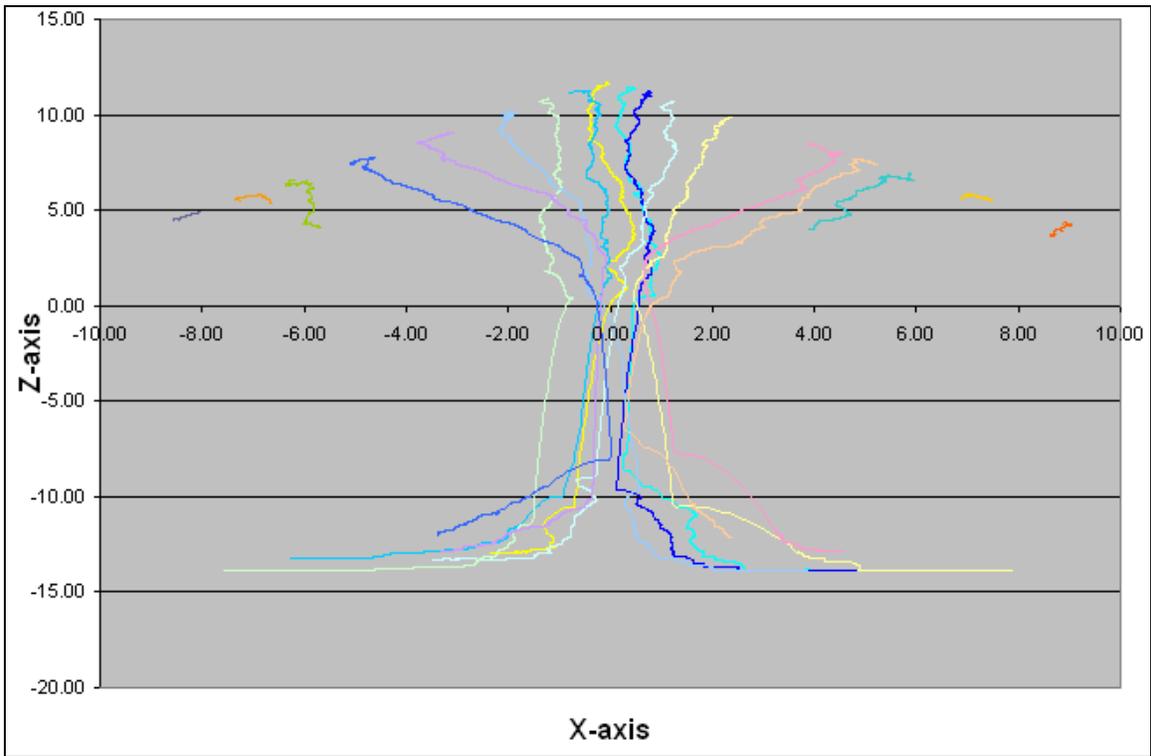


Figure 4.14 - X-Z particle displacement
12 m. stockpile / 2.0 m. discharge

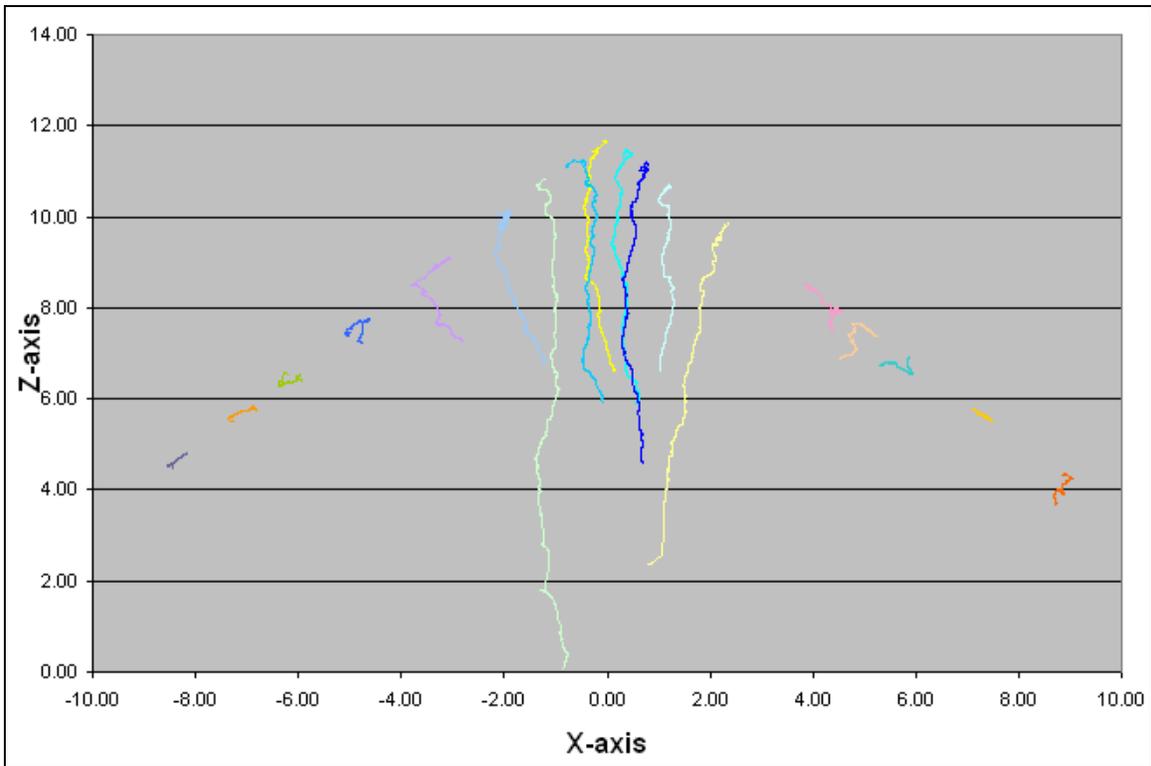


Figure 4.15 - X-Z particle displacement at discharge
12 m. stockpile / 2.0 m. discharge

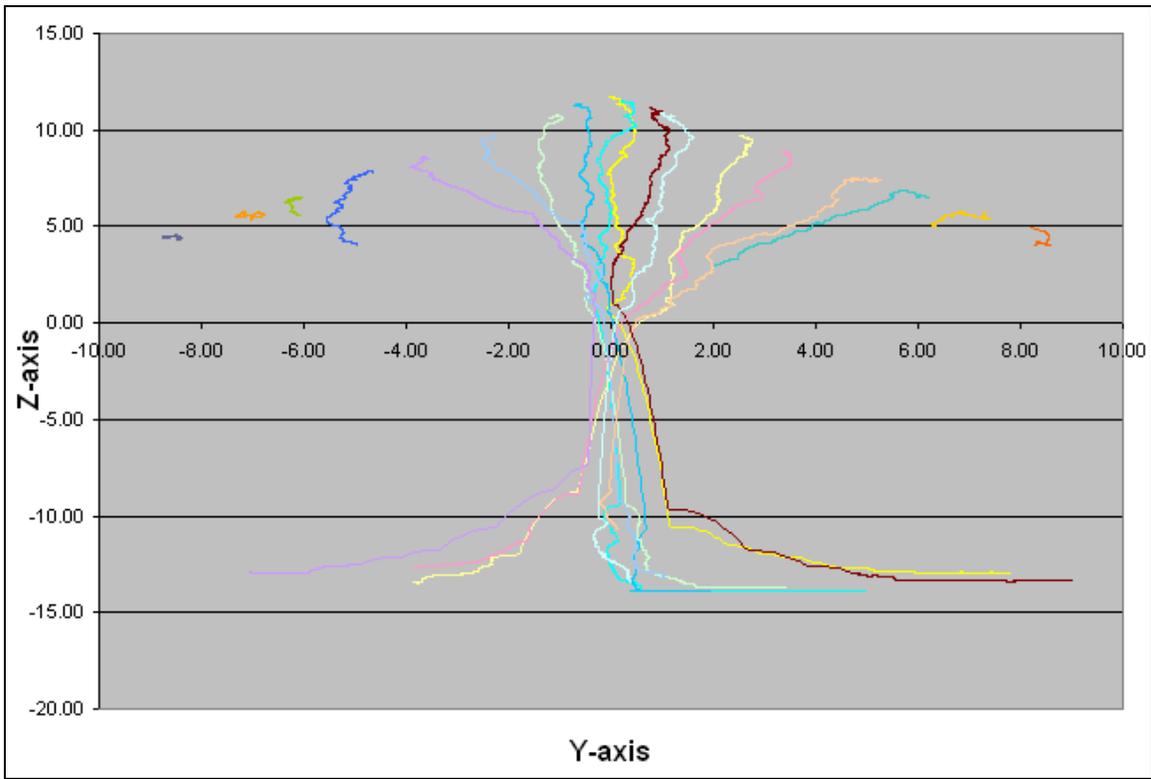


Figure 4.16 - Y-Z particle displacement
12 m. stockpile / 2.0 m. discharge

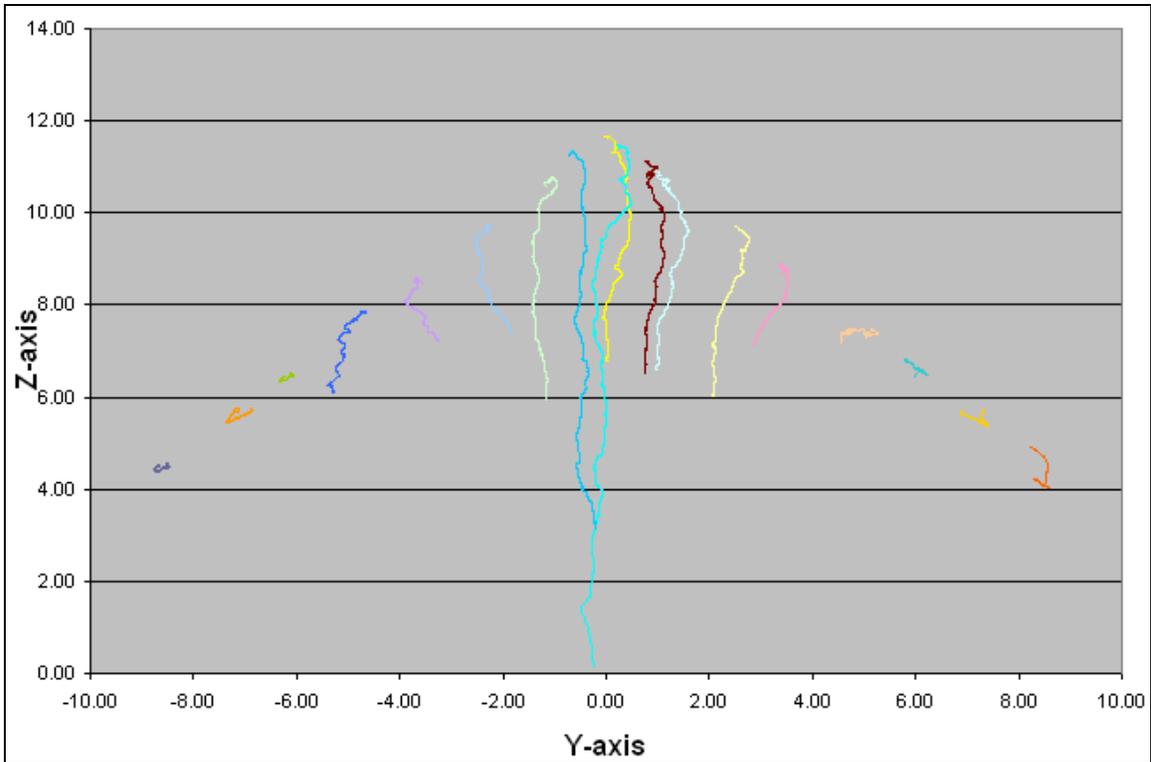


Figure 4.17 - Y-Z particle displacement at discharge
12 m. stockpile / 2.0 m. discharge

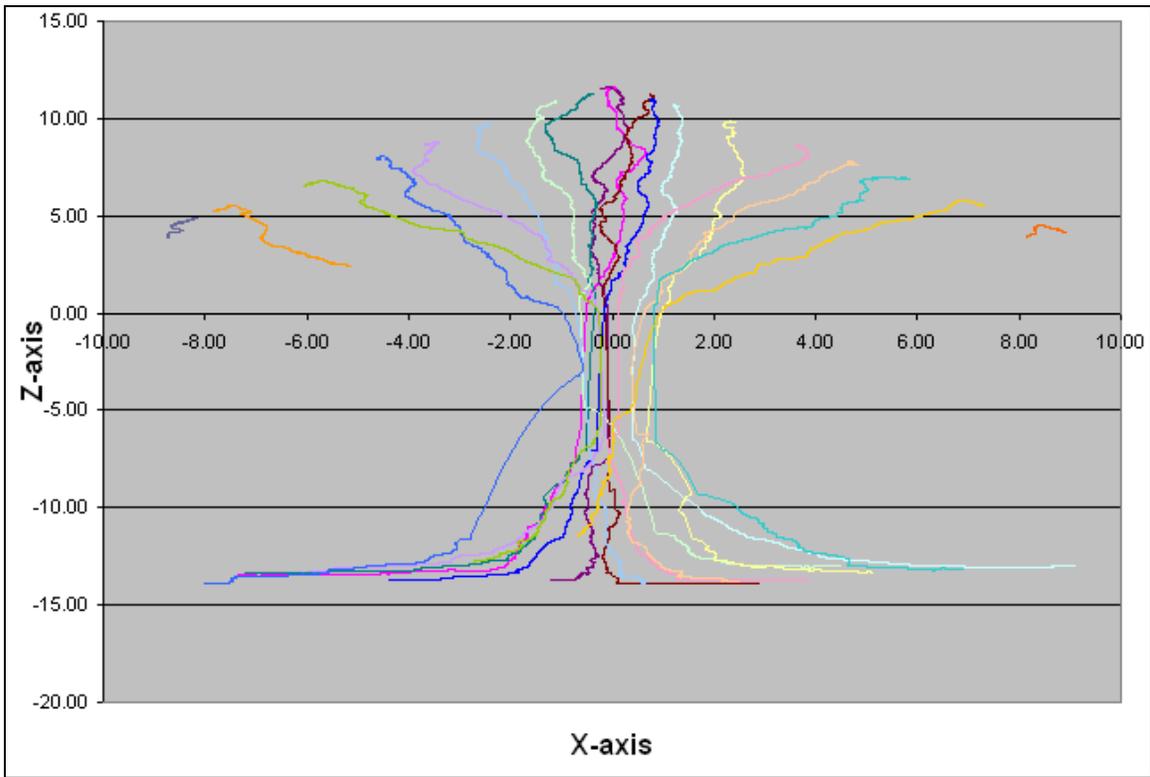


Figure 4.18 - X-Z particle displacement
12 m. stockpile / 2.5 m. discharge

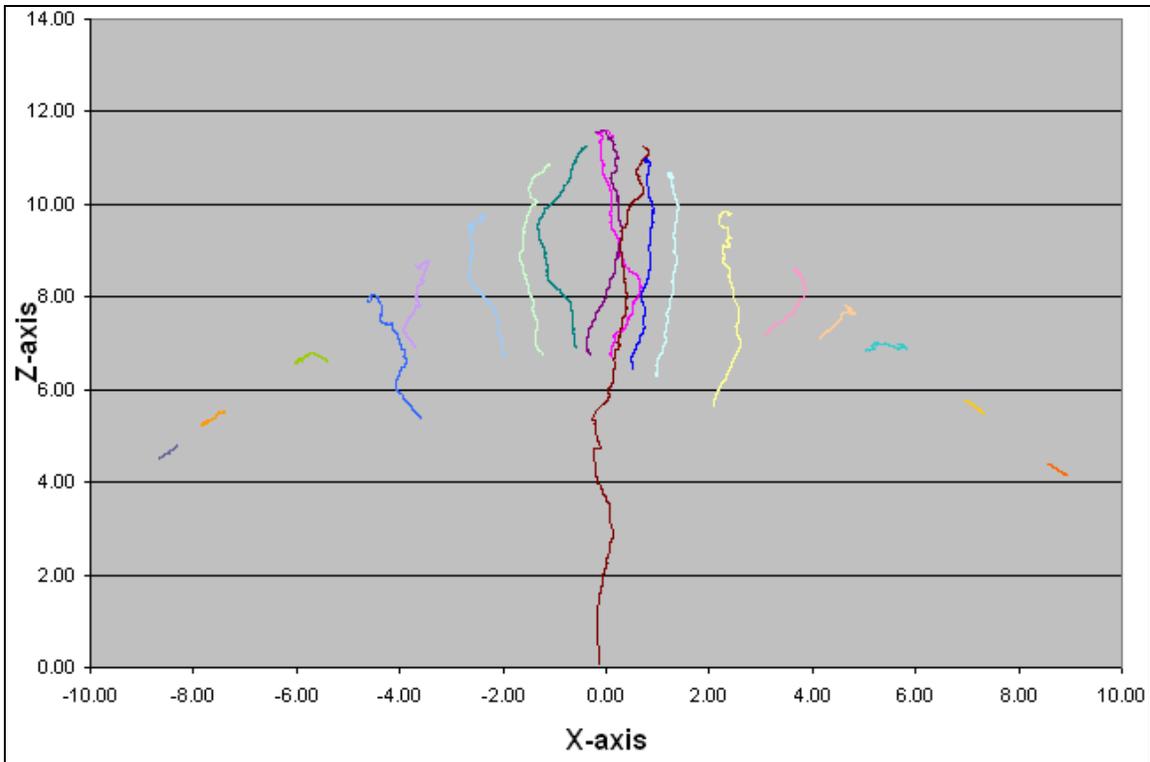


Figure 4.19 - X-Z particle displacement at discharge
12 m. stockpile / 2.5 m. discharge

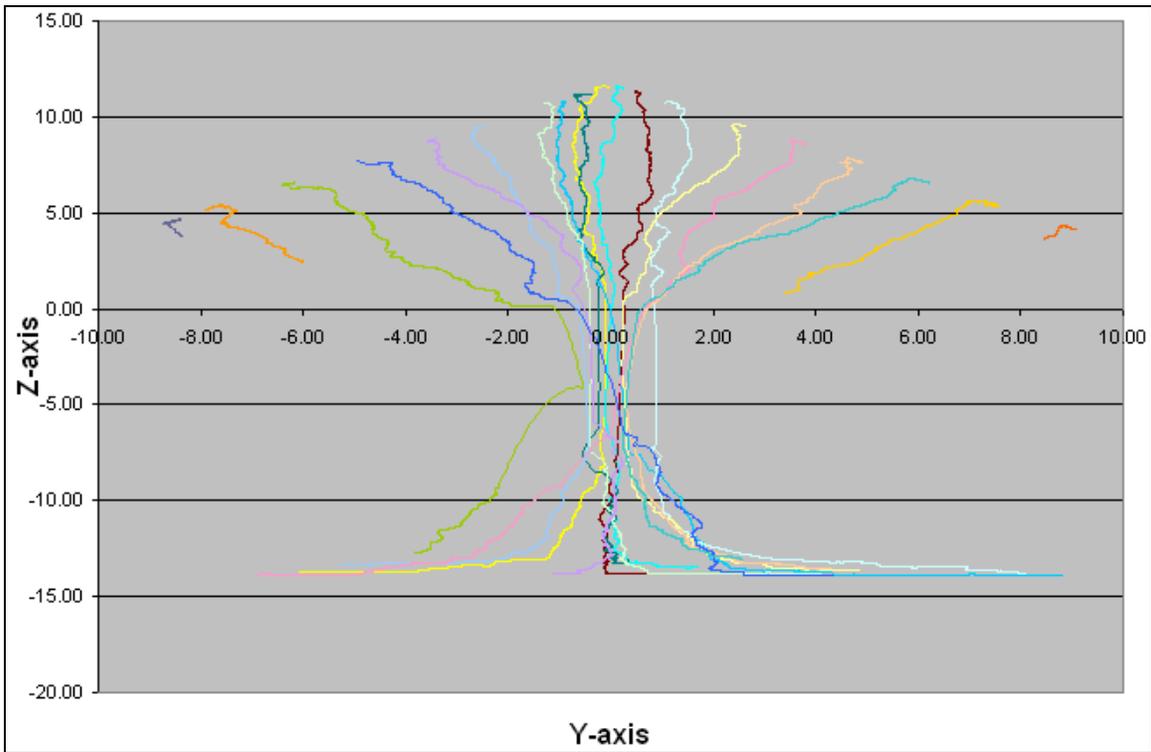


Figure 4.20 - Y-Z particle displacement
12 m. stockpile / 2.5 m. discharge

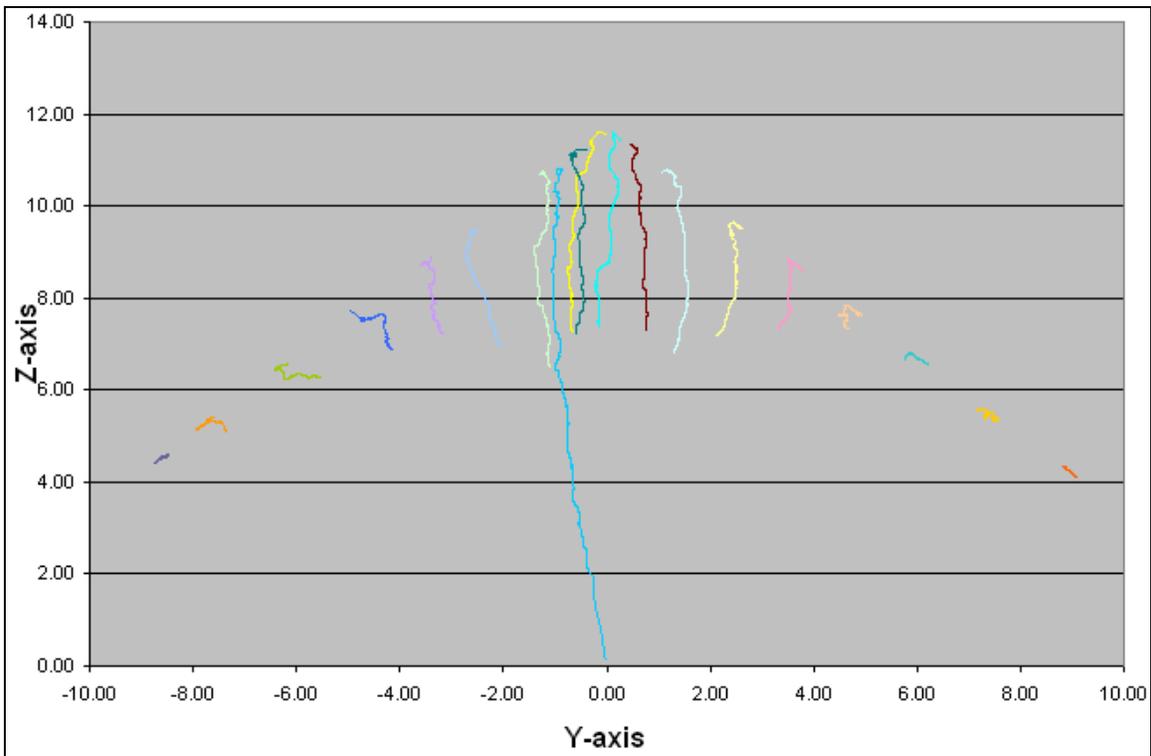


Figure 4.21 - Y-Z particle displacement at discharge
12 m. stockpile / 2.5 m. discharge

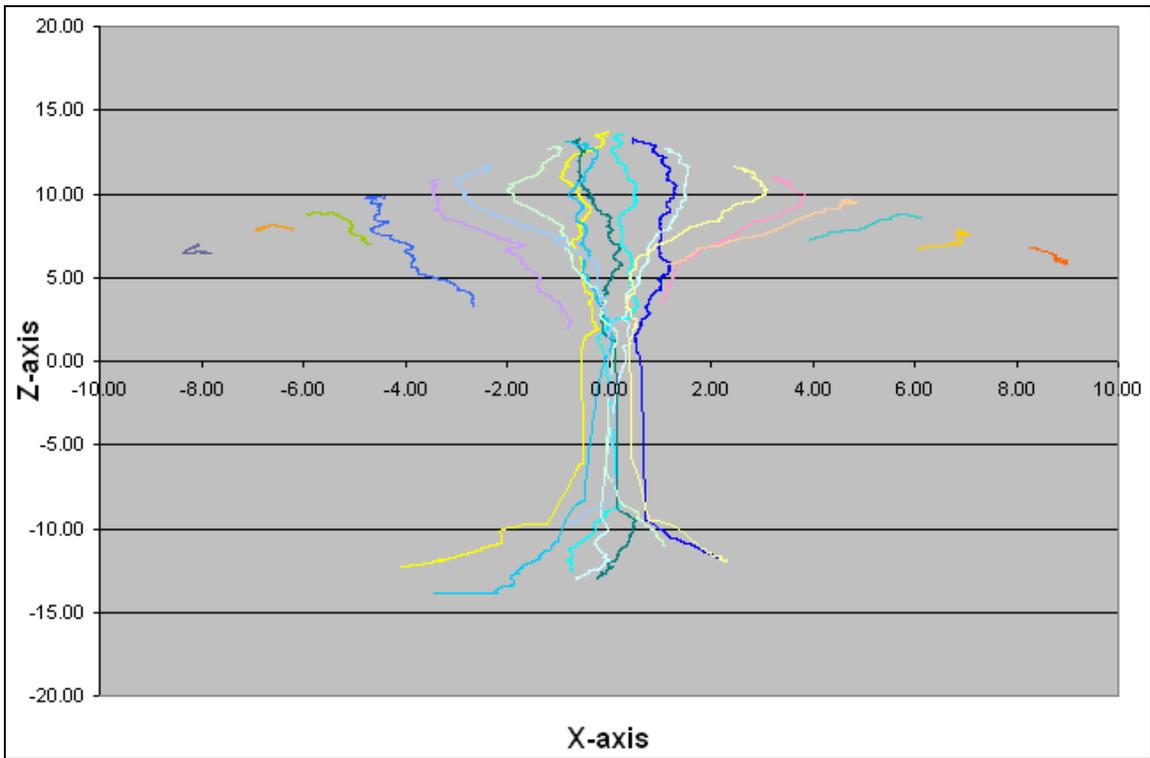


Figure 4.22 - X-Z particle displacement
14 m. stockpile / 2.0 m. discharge

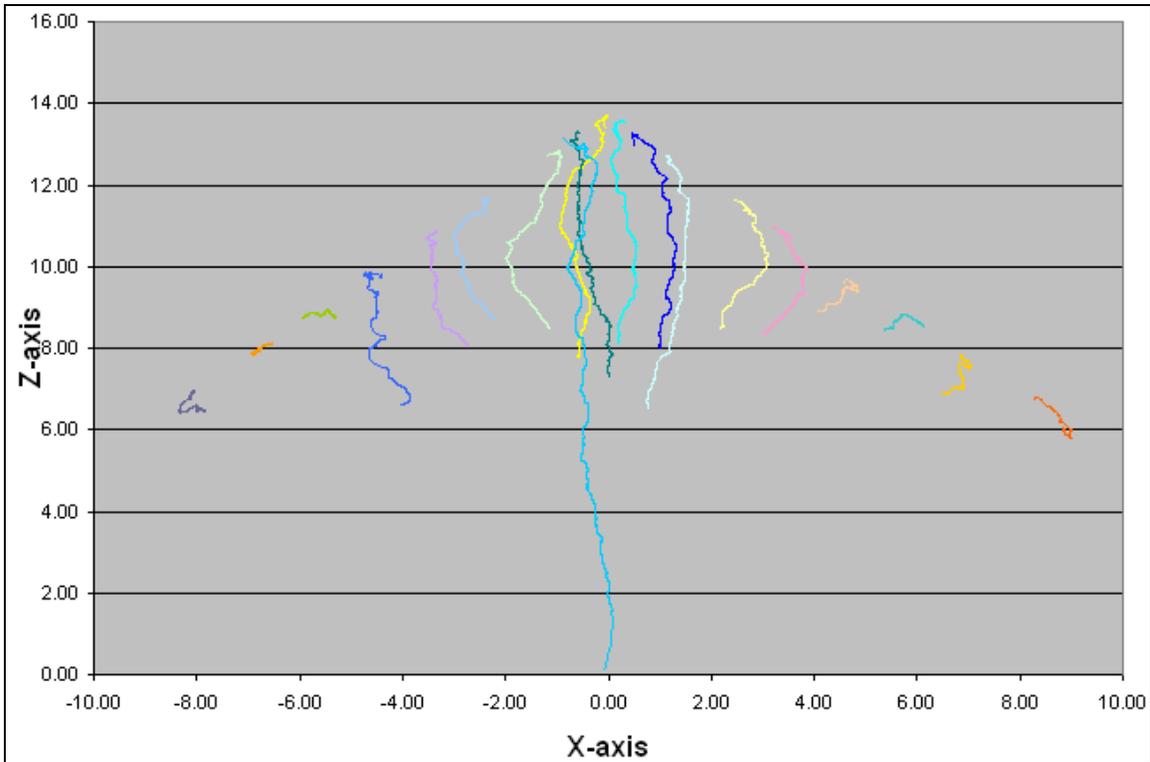


Figure 4.23 - X-Z particle displacement at discharge
14 m. stockpile / 2.0 m. discharge

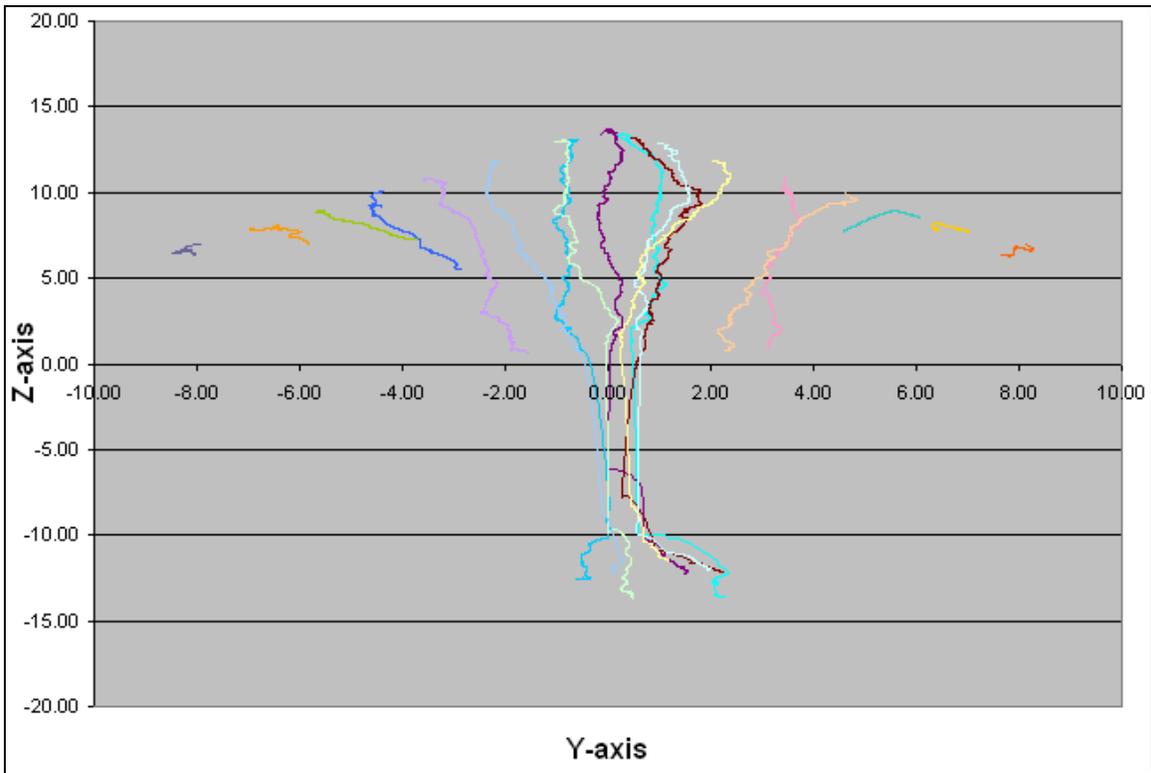


Figure 4.24 - Y-Z particle displacement
14 m. stockpile / 2.0 m. discharge

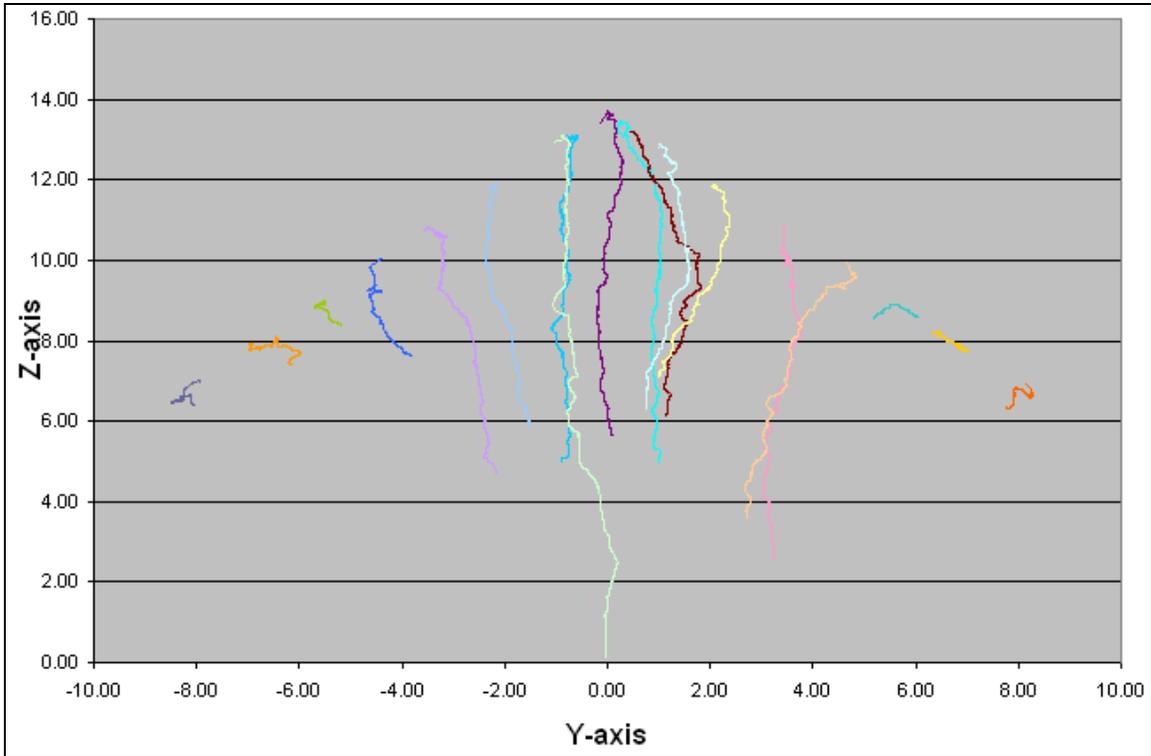


Figure 4.25 - Y-Z particle displacement at discharge
14 m. stockpile / 2.0 m. discharge

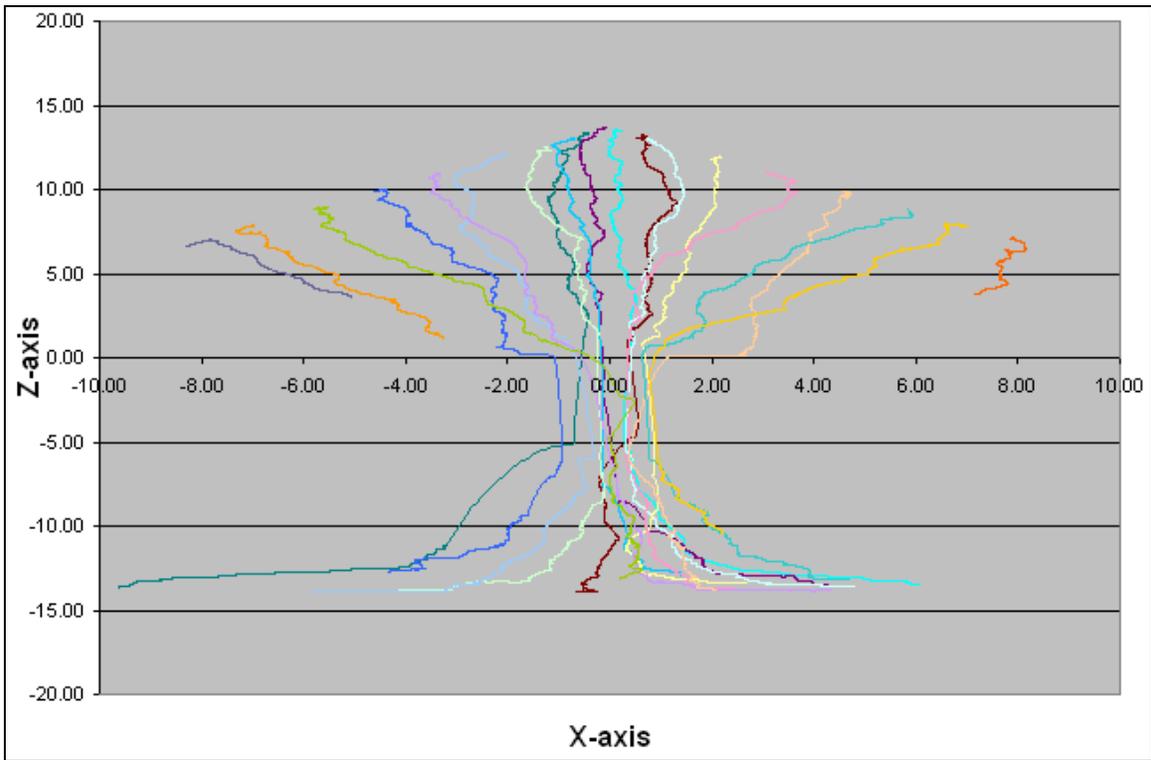


Figure 4.26 - X-Z particle displacement
14 m. stockpile / 2.5 m. discharge

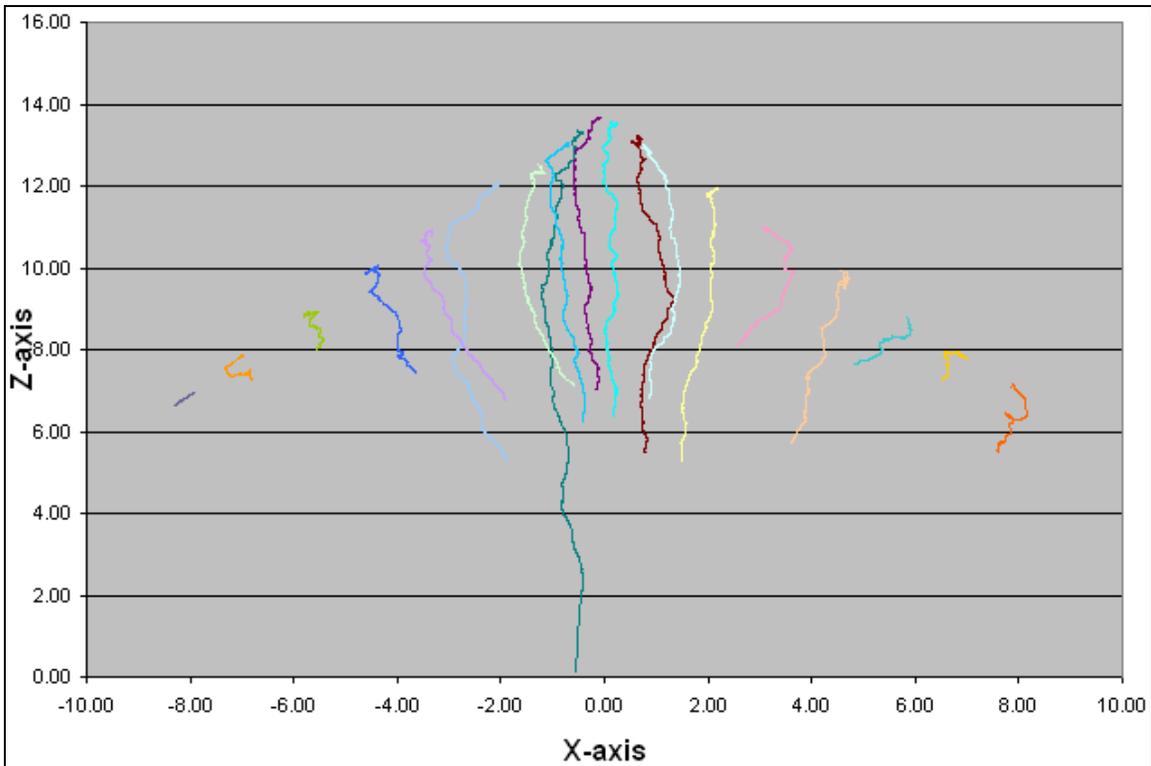


Figure 4.27 - X-Z particle displacement at discharge
14 m. stockpile / 2.5 m. discharge

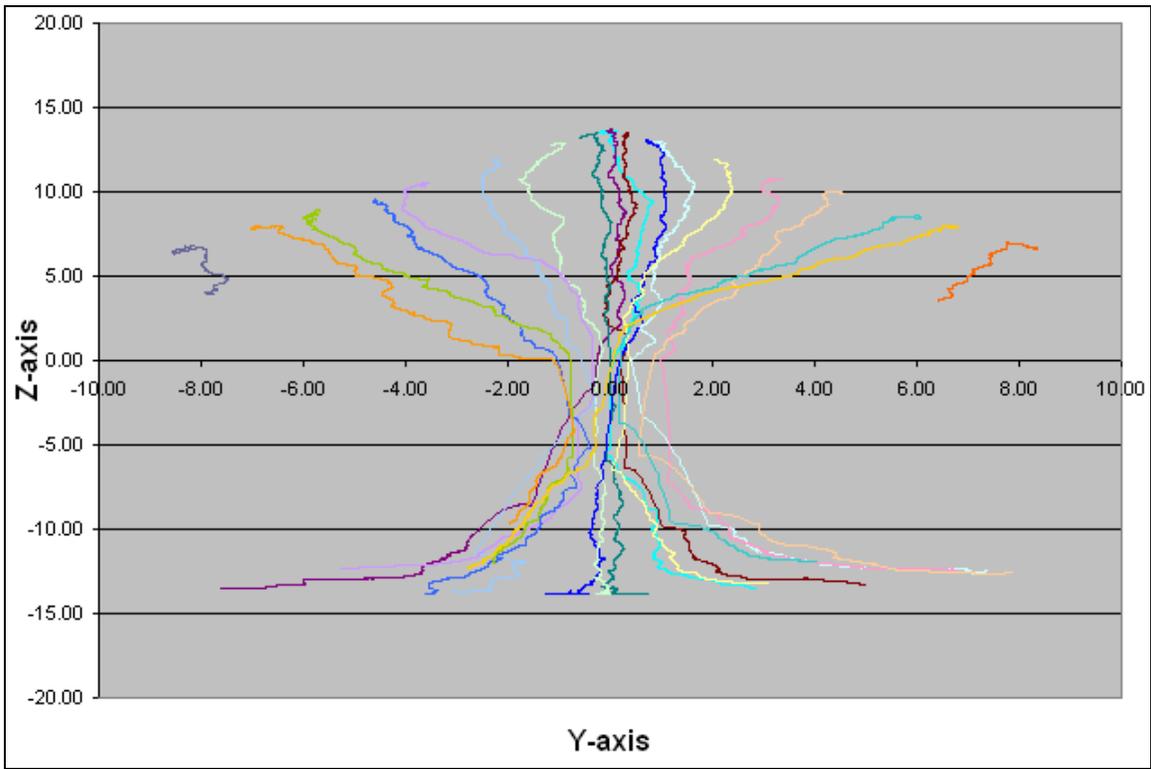


Figure 4.28 - Y-Z particle displacement
14 m. stockpile / 2.5 m. discharge

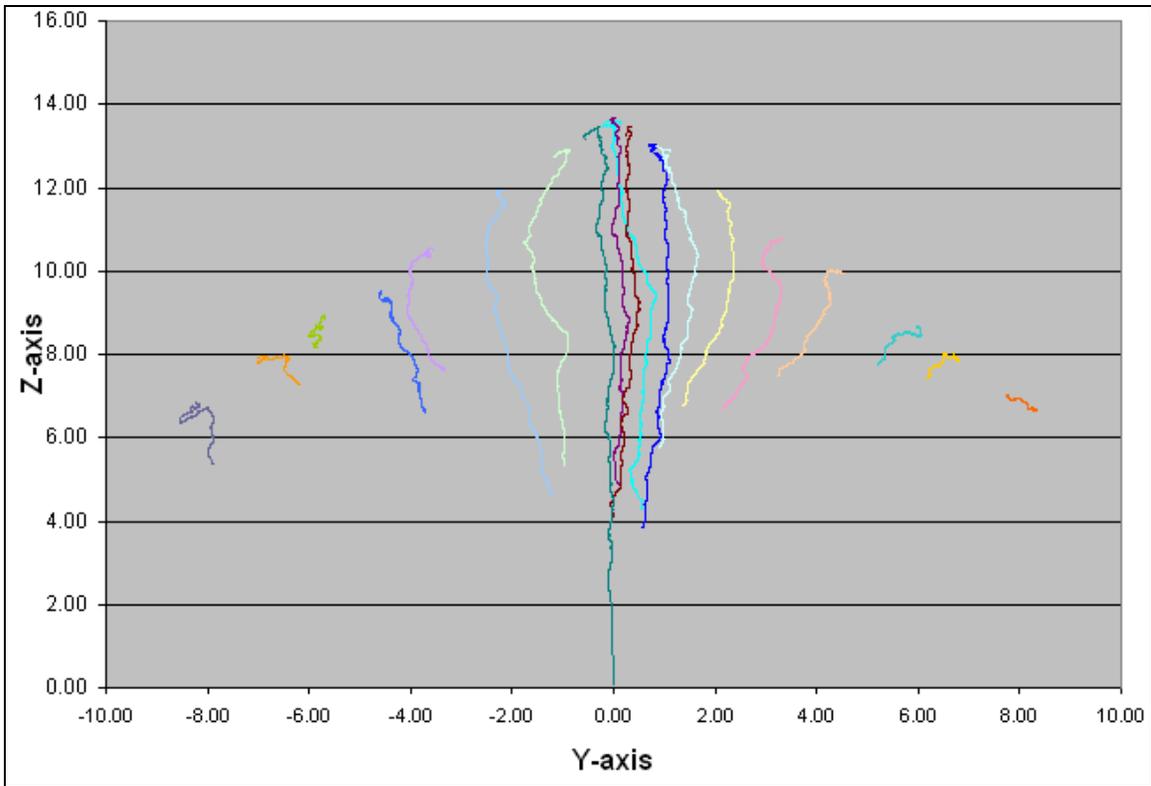


Figure 4.29 - Y-Z particle displacement at discharge
14 m. stockpile / 2.5 m. discharge

Figures 4.6 through 4.29 are all excellent visual examples of particle movement through a discharging stockpile. All simulations show a steep inner discharge cone forming at the top of the pile which over time expands outwards forming a wider, laterally shaped, discharge cone. It can also be seen how particles on the outer edges remain stationary and are less affected by other particle flow or by the initial particle movement due to the opening of the discharge point.

In addition to the general particle reactions during the simulation, the graphs which represent the “displacement at discharge” show how the particles move during the initial periods of the simulations. What is most noticed in these figures is how the particles closer to the center of the stockpile, directly above the discharge point, have traveled a greater distance over the short period of time in comparison to surrounding particles further away from the central discharge point. This is accurate with visual observations of actual discharging stockpiles.

Perhaps the greatest finding that has been determined from each simulation, and as represented in each of the previous graphs, is the consistency between each stockpile and discharge size. While simulations on the larger stockpiles and smaller, 2.0 meter, discharge opening took longer in comparison to the smaller stockpiles with larger openings, each stockpile simulation produced similar particle movement results with consistent visual representations.

2.3.1. Particle Velocities During Simulation

In addition to the X-Z and Y-Z displacement graphs, velocity graphs were developed in order to compare the change in velocities of selected particles during the complete simulation. As can be seen in the following graphs, three particles were selected for monitoring for each representative stockpile size and opening (12 meter/ 2.0 meter opening stockpile has no velocity data). In each graph, the larger the circle size, the higher the velocity of that particle at that respective particle location. In addition, the particle at the peak of the stockpile at the start of the each respective simulation was graphed over the course of the simulation showing the change in velocity based only on Z-axis location, or vertical placement, within the stockpile during the simulation.

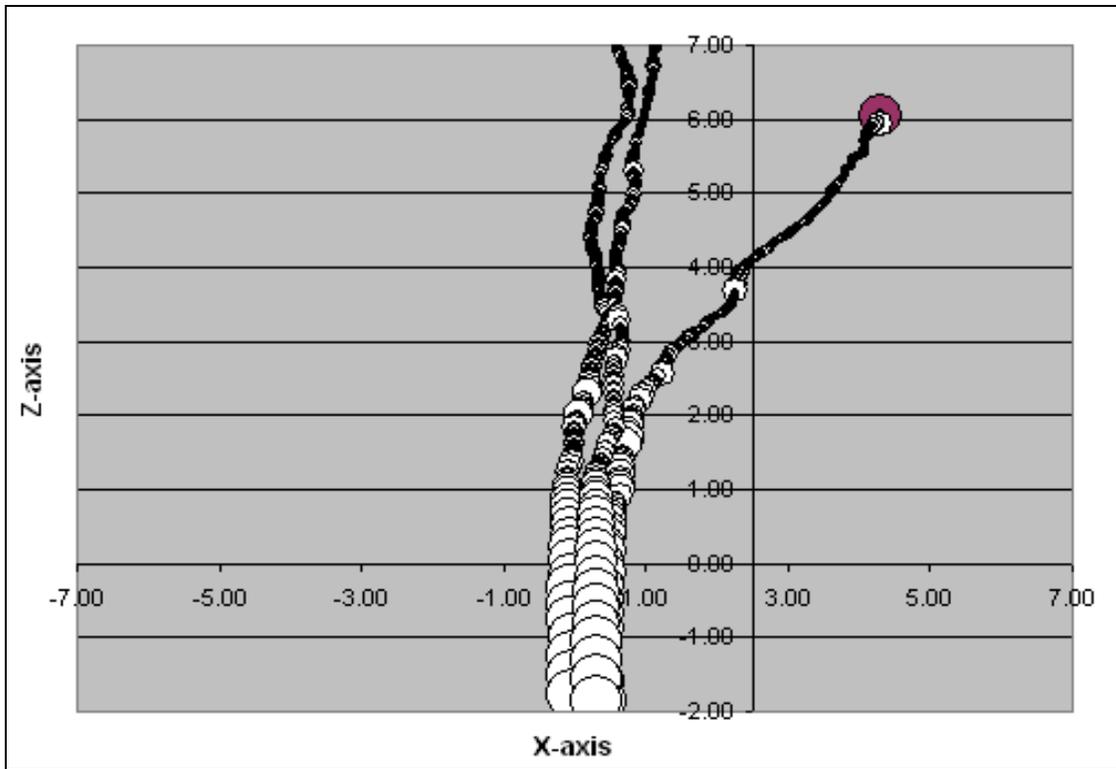


Figure 4.30 - X-Z change in particle velocity for three particles during simulation
10 m. stockpile / 2.0 m. discharge

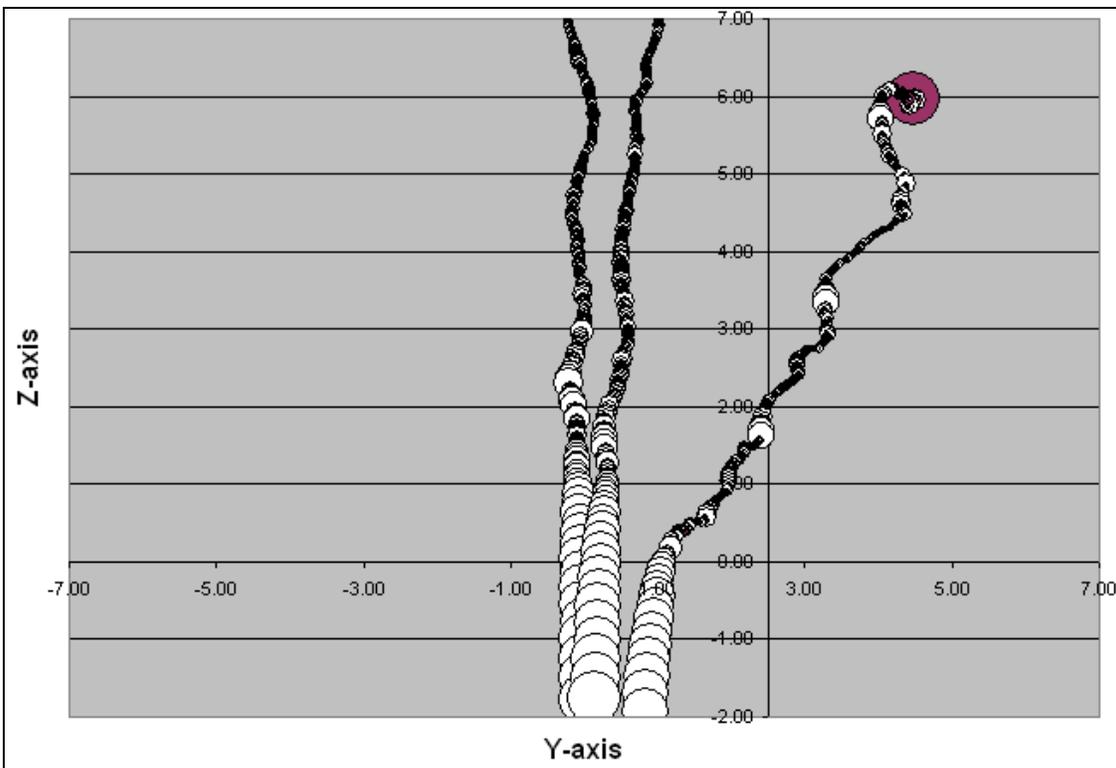


Figure 4.31 - Y-Z change in particle velocity for three particles during simulation
10 m. stockpile / 2.0 m. discharge

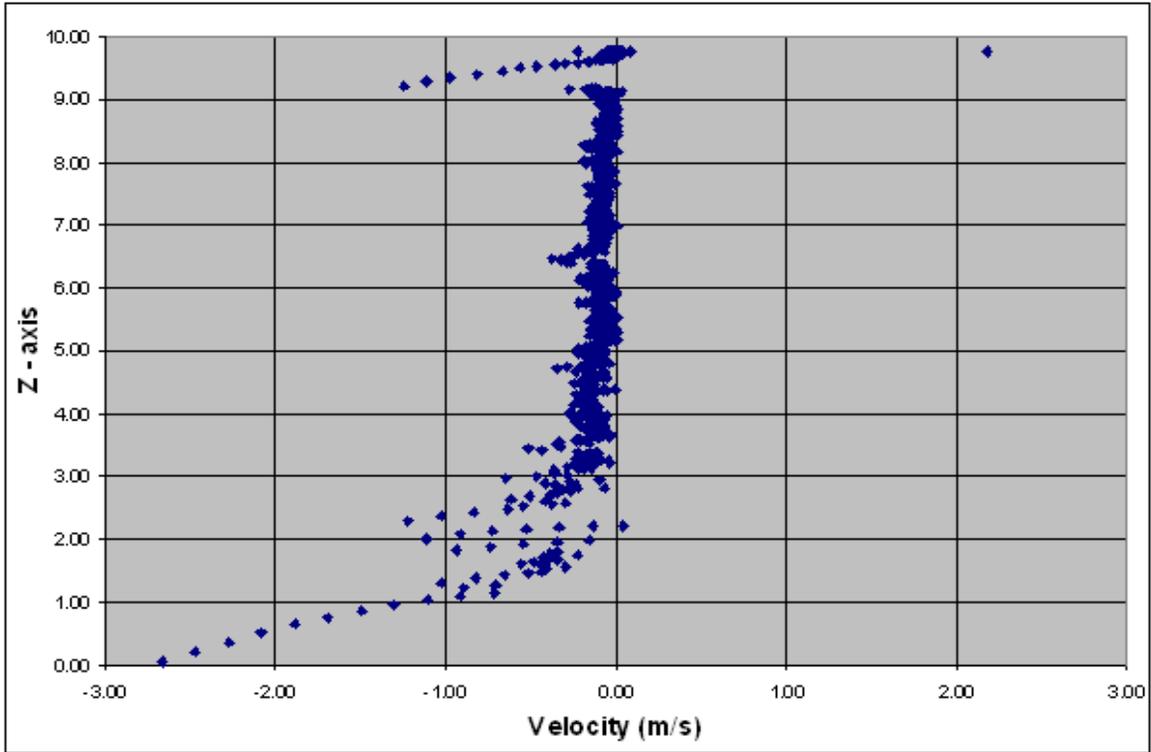


Figure 4.32 - instantaneous velocity during simulation at particle Z-axis location
10 m. stockpile / 2.0 m. discharge

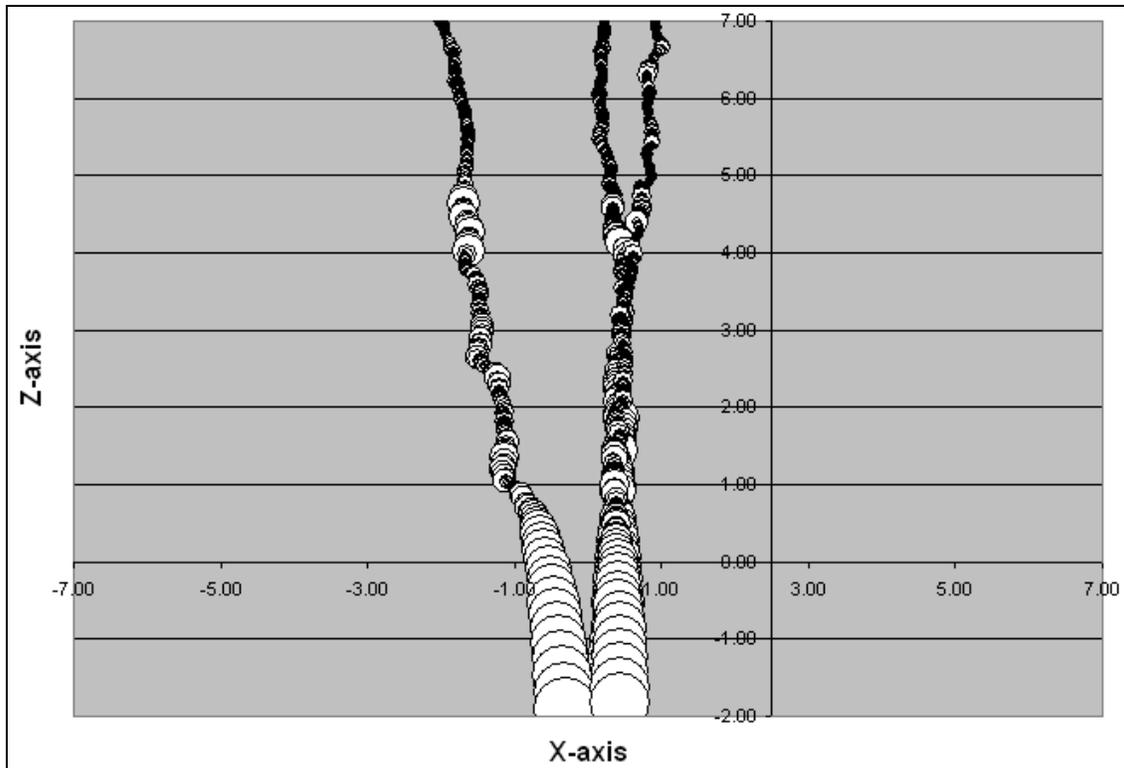


Figure 4.33 - X-Z change in particle velocity for three particles during simulation
10 m. stockpile / 2.5 m. discharge

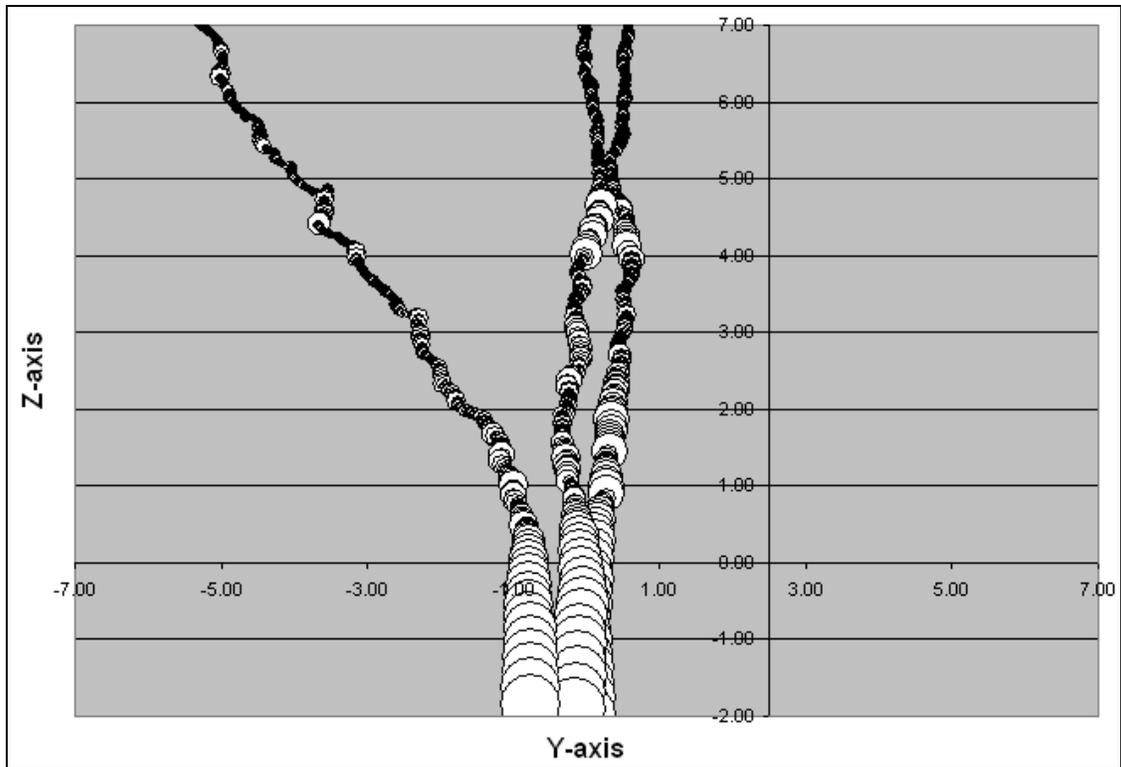


Figure 4.34 - Y-Z change in particle velocity for three particles during simulation
10 m. stockpile / 2.5 m. discharge

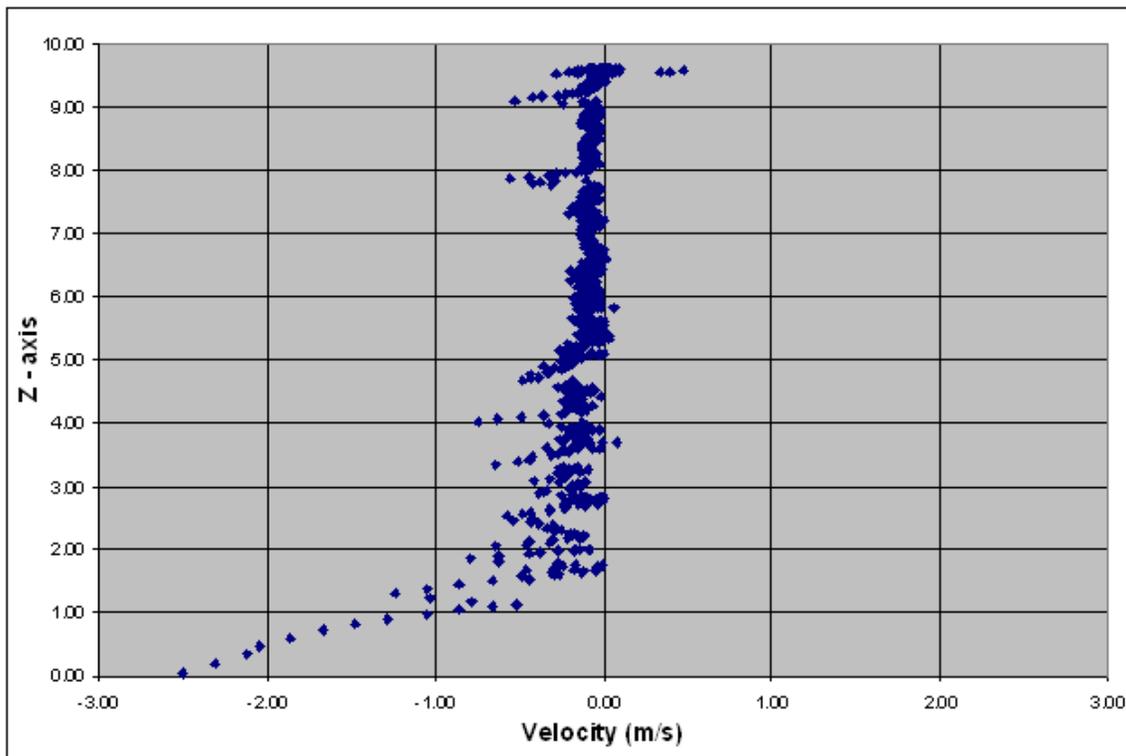


Figure 4.35 - instantaneous velocity during simulation at particle Z-axis location
10 m. stockpile / 2.5 m. discharge

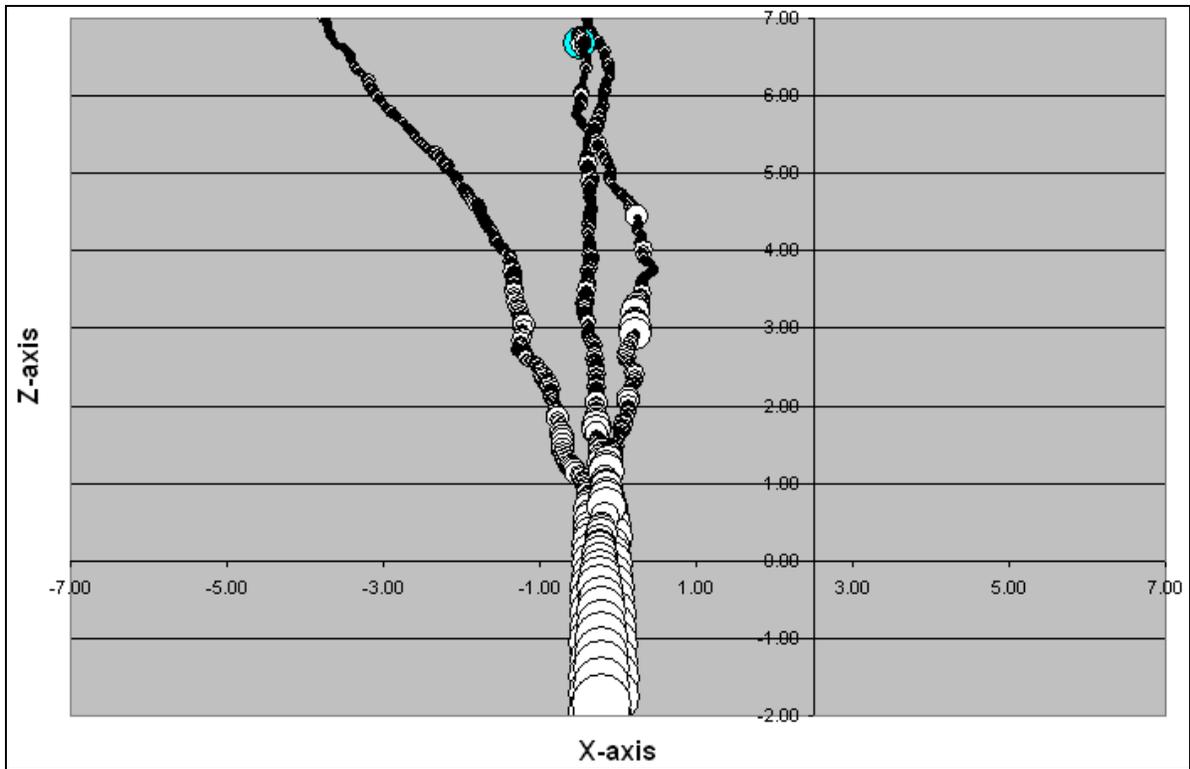


Figure 4.36 - X-Z change in particle velocity for three particles during simulation
12 m. stockpile / 2.5 m. discharge

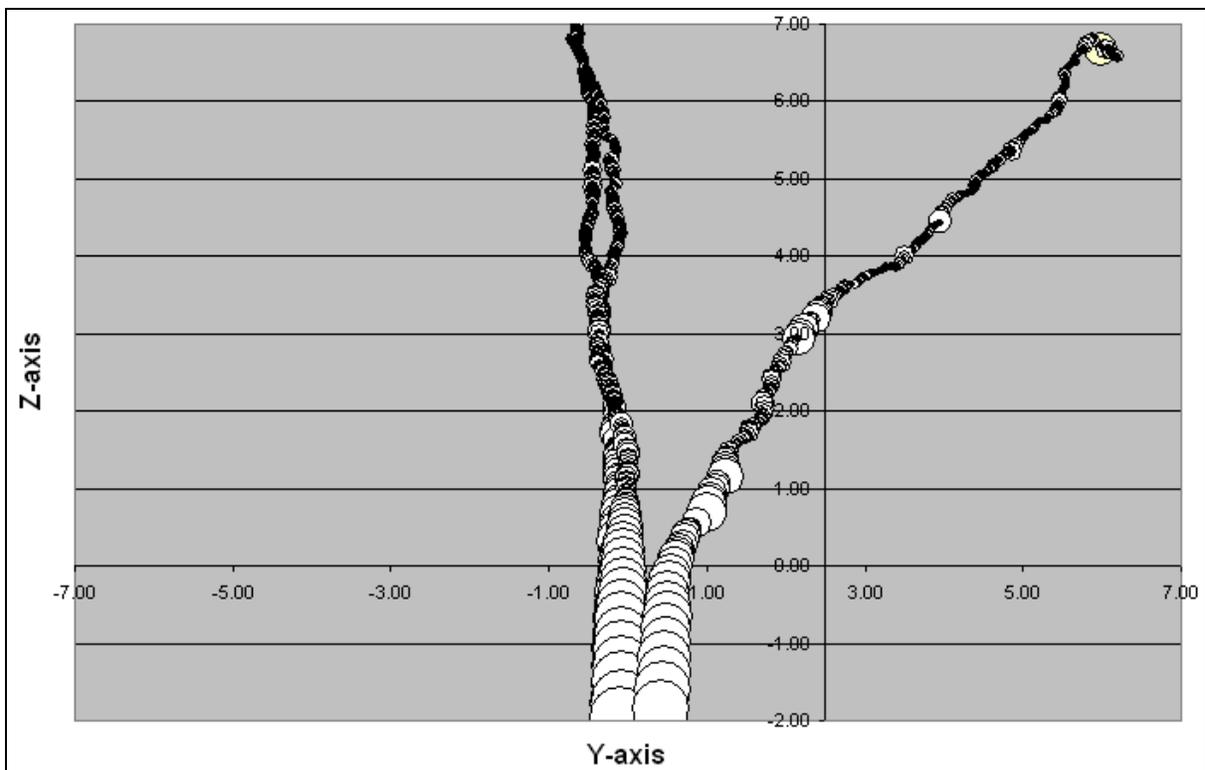


Figure 4.37 - Y-Z change in particle velocity for three particles during simulation
12 m. stockpile / 2.5 m. discharge

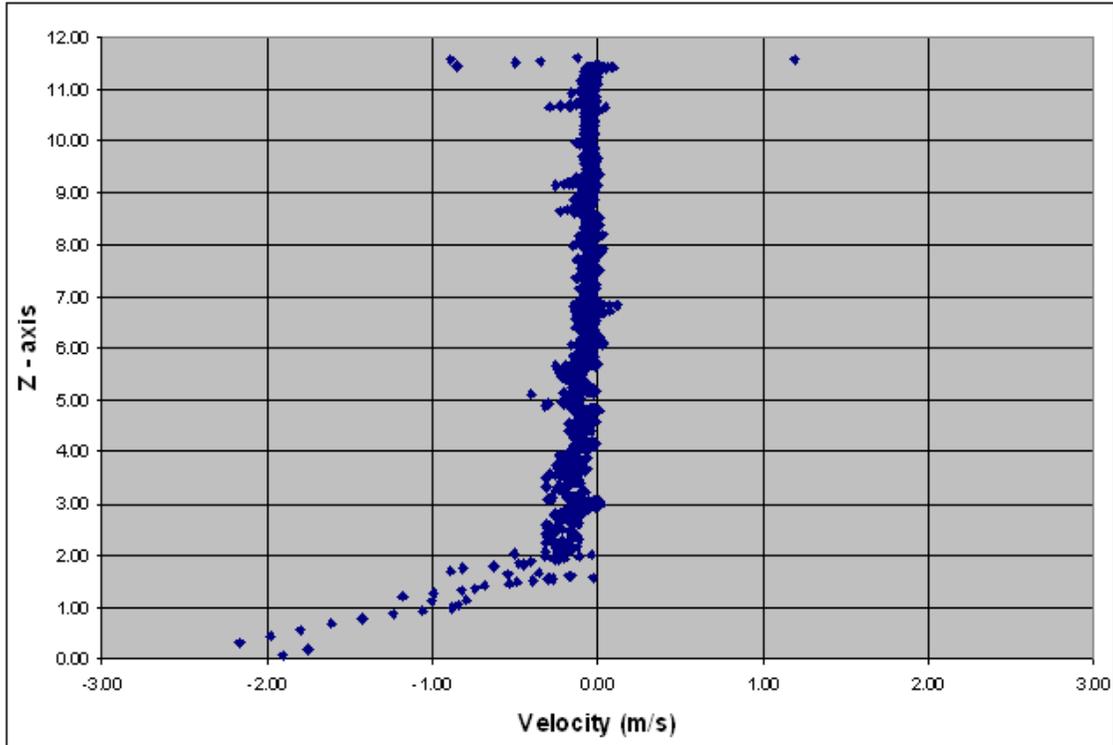


Figure 4.38 - instantaneous velocity during simulation at particle Z-axis location
12 m. stockpile / 2.5 m. discharge

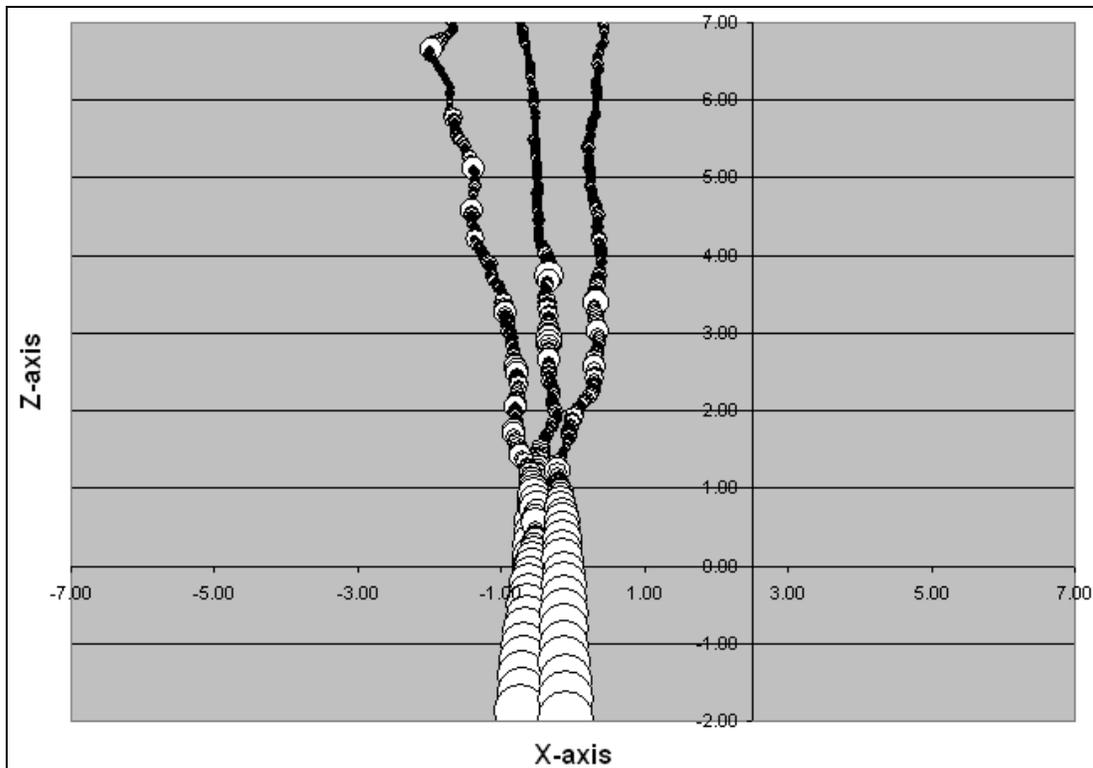


Figure 4.39 - X-Z change in particle velocity for three particles during simulation
14 m. stockpile / 2.0 m. discharge

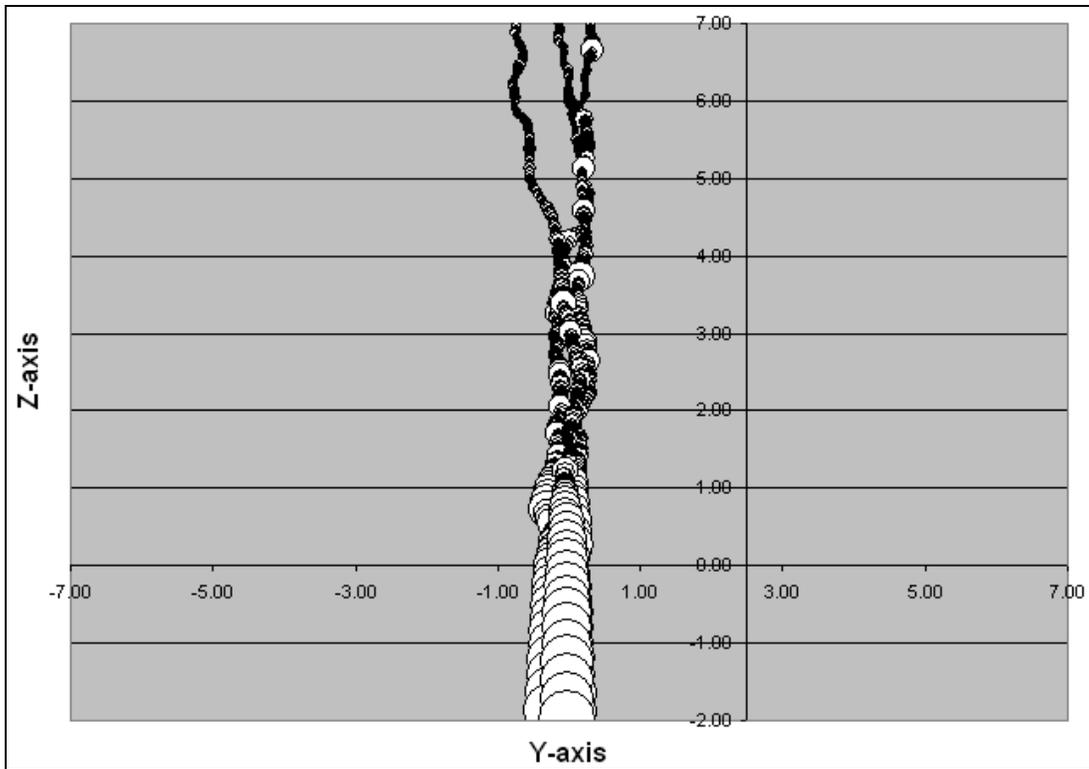


Figure 4.40 - Y-Z change in particle velocity for three particles during simulation
14 m. stockpile / 2.0 m. discharge

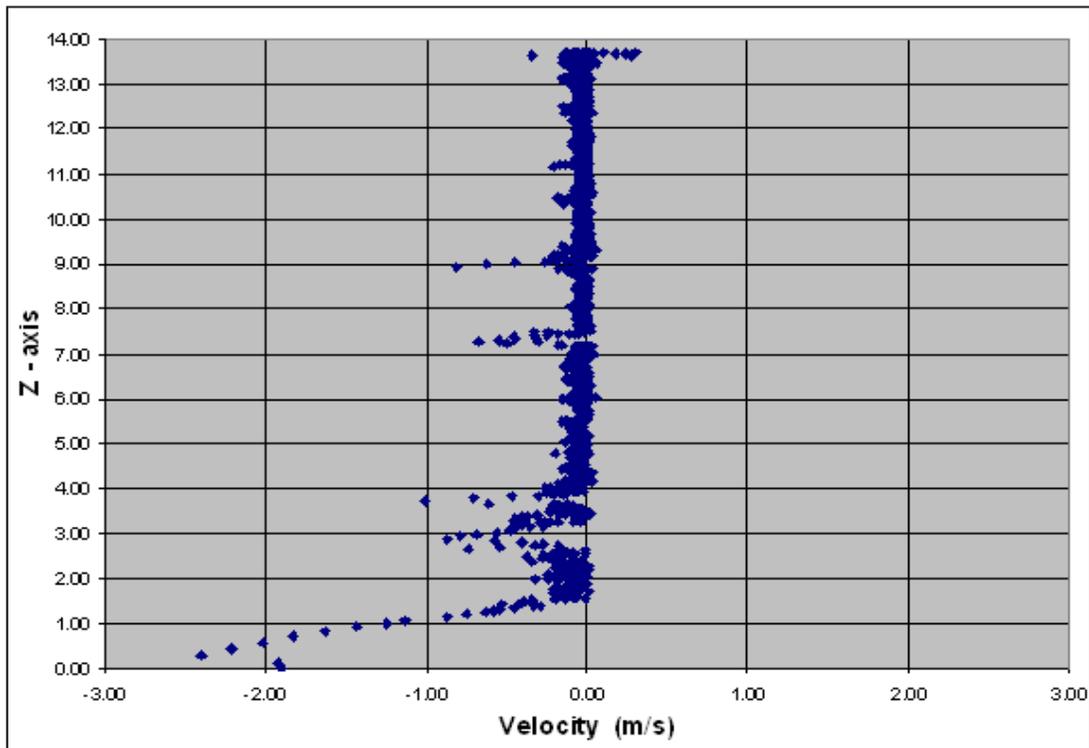


Figure 4.41 - instantaneous velocity during simulation at particle Z-axis location
14 m. stockpile / 2.0 m. discharge

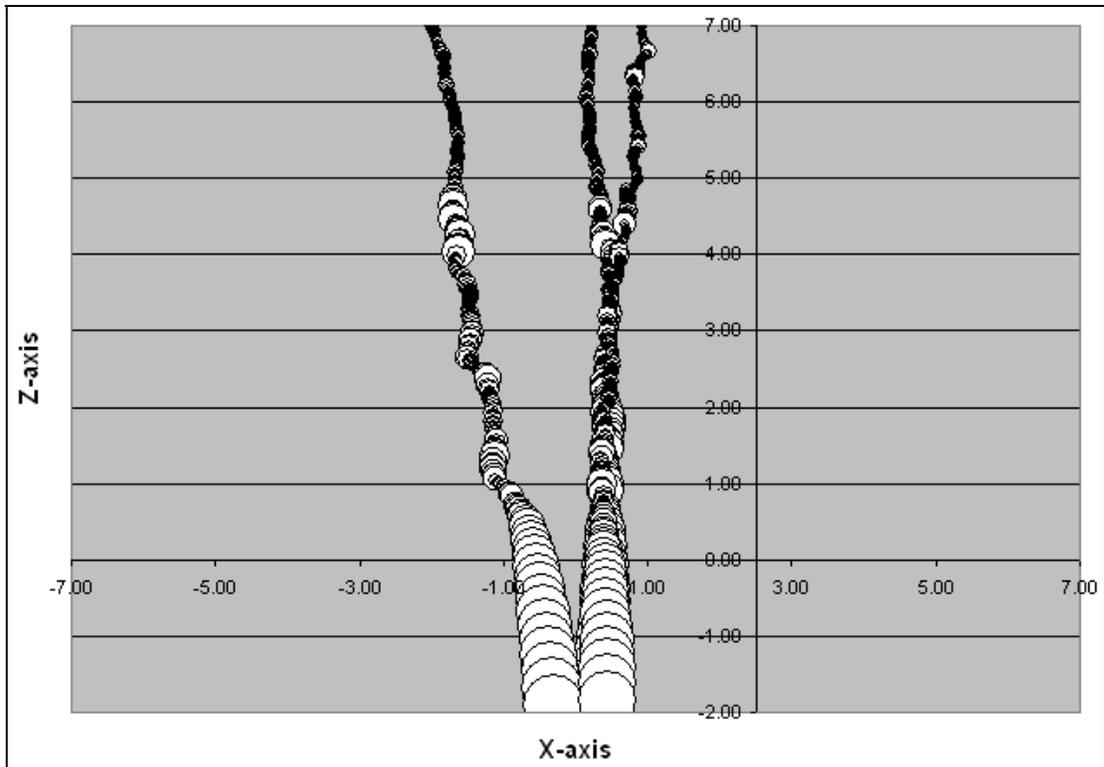


Figure 4.42 - X-Z change in particle velocity for three particles during simulation
14 m. stockpile / 2.5 m. discharge

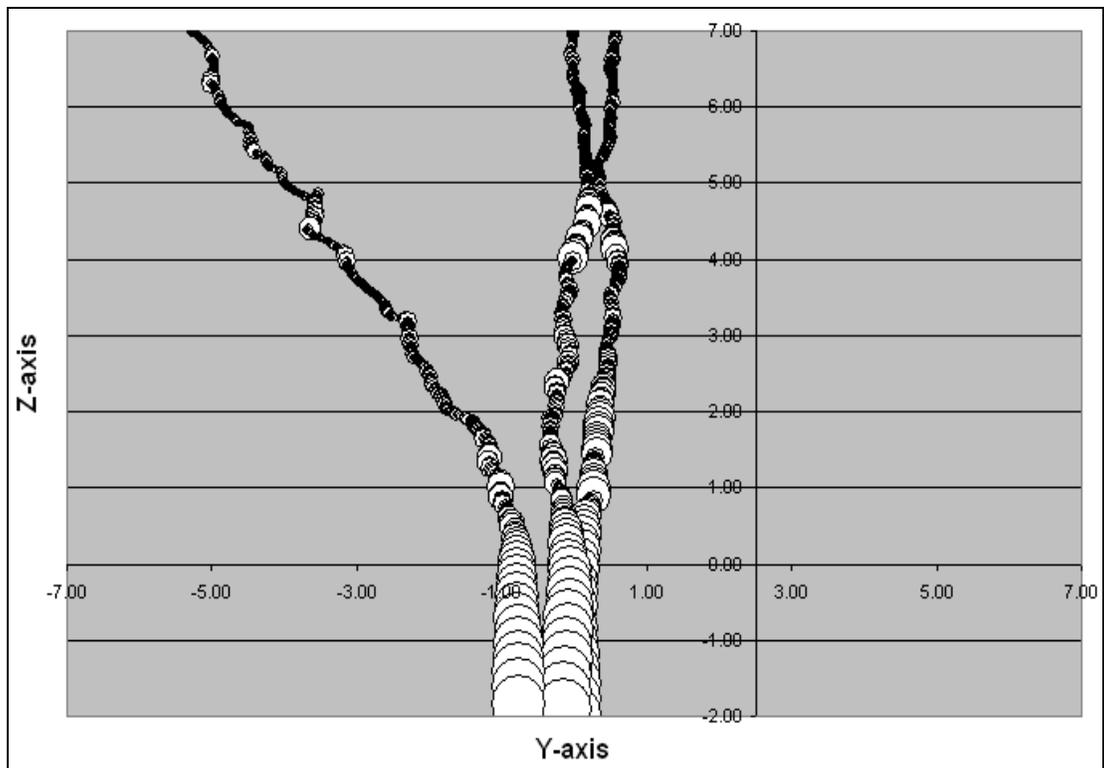


Figure 4.43 - Y-Z change in particle velocity for three particles during simulation
14 m. stockpile / 2.5 m. discharge

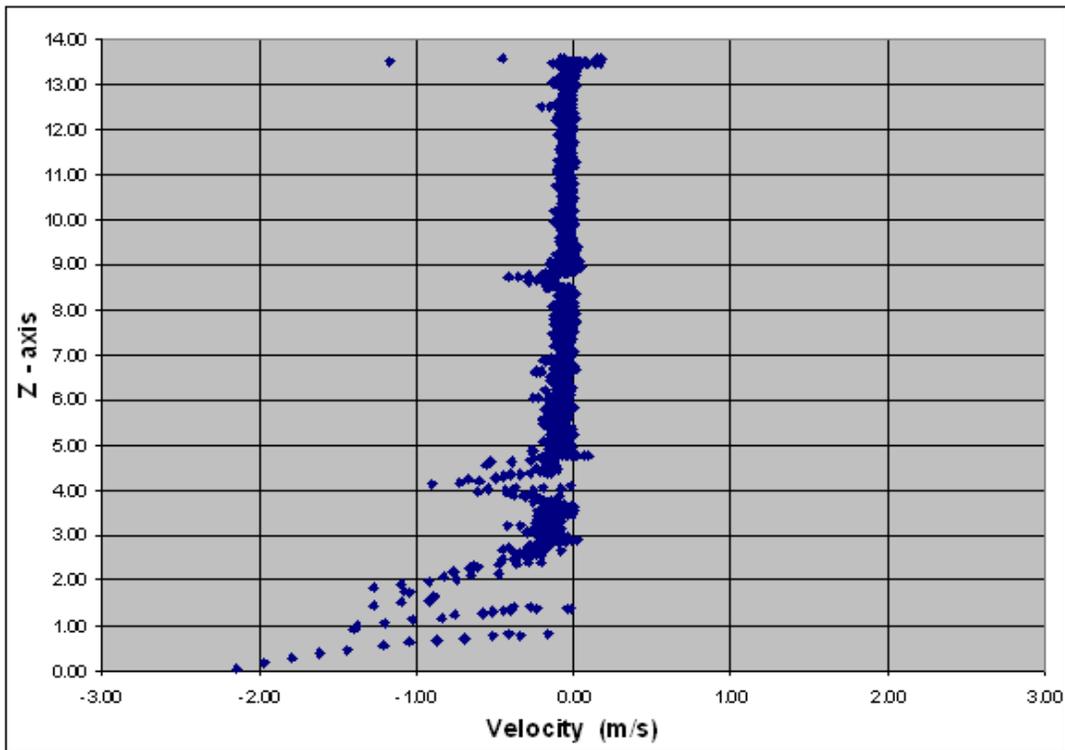


Figure 4.44 - instantaneous velocity during simulation at particle Z-axis location 14 m. stockpile / 2.5 m. discharge

Figures 4.30 through 4.44 all provide excellent visual representations of the change in velocities over the course of the simulations. As seen for each “change in particle velocity for three particles during simulation” graph, particles tend to travel through the stockpile at a consistent velocity until they reach 1.5 to 3.0 meters from the discharge point. At this point, the particle velocity increases as the particle begins exiting the pile with less surrounding obstructions. Each respective graph provides similar results regarding general particle velocity over the course of the simulation.

What can also be observed within each “change in particle velocity for three particles during simulation” graph are instances where particles randomly increase velocity within the center of the pile during simulation. While there is no way to determine the reason for this occurrence, it is believed that the particles increase velocity suddenly over time due to the formation of pockets within the stockpile. The increase in velocity is a result of the sudden release of each particle from its stationary location. This pocketing occurrence, known as “arching” or “bridging,” occurs in stockpiles due to either particles locking together because the stockpile is represented of large rocks in relation to the discharge size or because the particles pack together at a point above the outlet, forming an obstruction (Maynard 2004). During each

simulation, either case could have existed as sudden velocity increase can be seen at various locations along each pile for both 2.0 and 2.5 meter discharge sizes.

Each “instantaneous velocity during simulation at particle Z-axis location” graph provides a more representative review of velocity as the peak particle travels closer to the discharge point. These graphs show results similar to the “change in particle velocity for three particles during simulation” graphs, however they also provide a value to the velocity of the peak particle. As seen for each graph, the particles being tracked tend to increase in velocity between 2.0 and 3.0 meters above the pile discharge point. In many cases, the velocity reaches 2.0 meters per second near the discharge location. This observation leads the belief that the particles are actually beginning to free fall prior to discharging from the stockpile. While this may be an accurate representation of round particles flowing through a large discharge point, it is believed to be an inaccurate depiction of the velocity of rocks exiting a stockpile via a discharge point. The trend as can be seen in each graph, however, may represent the actual trend in which rocks travel while exiting a stockpile, only with a much lower velocity during the course of discharge.

3. Conclusions

After analyzing the graphs created from the data provided by the simulations, much can be determined. The particle displacement graphs provided what was believed to be an accurate representation of how particles moved through a discharging stockpile. Mainly, particles traveled from their point of origin towards the discharge point in a fashion representative of what is viewed of actual discharging stockpiles. Considering no known detailed study has yet to be performed which traces detailed particle movement through a pile, a visual comparison is the best known analysis for comparison. In addition, the particle displacement simulation results showed that particles closer to the center of the stockpile, directly above the discharge point, traveled faster through the pile than particles which began further down the outslopes of the stockpile. These results even held true for particles which began at the peak of the pile, further away from the discharge point than some of the particles further down the outslopes of the stockpile. Overall, these findings are accurate with visual observations and are also accurate with findings from the Residence Time Distribution (RTD) analysis discussed in Chapter 3.

Velocity graphs created from the simulation data also provided essential information necessary in better understanding how particles travel within a discharging stockpile. As seen on all velocity simulation graphs, particles tended to travel at a consistent velocity until 2.0 to 3.0 meters away from the discharge point. While the velocities recorded are believed to be in excess of the actual velocities of rocks traveling through a discharging stockpile, the velocity trend is believed to be accurate. Another key finding is what is believed to be “arching” within the stockpile flow simulations. While the data collected from these simulations provides little

information as to why particles were suddenly increasing in velocity at various locations in the pile, it provides promising information that may be essential to future studies.

Overall, the information collected from these simulations can be deemed an important step in developing simulations capable of mapping particle flow consistent with actual discharging rock stockpiles. Theoretically, the simulations provided accurate results consistent with how stockpile are expected to react during discharge. In addition to accurate results, the graphs proved the consistency of the simulations and the reliability of the PFC3D program. While this data cannot directly be used to predict residence time within a stockpile or the likelihood of arching within a stockpile, it does prove that PFC3D is capable of providing accurate flow representations of discharging stockpiled material. Future analysis should include particles more accurately shaped along with a discharge point which operates similar to that of an actual stockpile discharge feeder. Combining these points into a simulation while also being able to collect empirical data from a stockpile similar in size and design will allow for a direct comparison to be made, possibly resulting in equations capable of predicting both flow and safety issues which may be encountered while discharging from stockpiles of any shape.

Chapter 5: Final Summary and Conclusions

1. Summary

Stockpiles are used throughout mining over other storage methods because of the various loading/unloading techniques and the ability to actually store the rock using this method. Silos, and other storage devices, are an unnecessary added cost which is needed only if the material to be stored is toxic, flows freely, or requires a special discharge technique. While there are many obvious reasons to chose stockpiling over other aggregate rock storage techniques, there is little known on how particles actually travel through a bottom discharging stockpile.

The research of today regarding stockpiles focuses on overall improvements regarding blending and final product. Information pertaining to how a stockpile reacts during a discharging procedure is lacking. Both horizontal and vertical movement has been expected to exist in a pile, but exactly how the particles move during discharge has always been unknown. This paper provides results regarding displacement and velocity to be expected in an actual discharging stockpile.

While the results found in this paper are raw, they do prove the capability to both map and predict displacement based on particle location in a stockpile. Increased information on these findings can assist many in obtaining a better understanding on how stockpiles perform during bottom discharge procedures. This information may lead to better sampling, safer stockpiles and increased understanding on when to make proper process adjustments based on incoming rock parameters.

2. Conclusions and Future Recommendations

Based on the results compiled from Chapter 3, many conclusions can be made. Overall, it was determined that the aggregate stockpile discharges similar to that of a plug flow system. It was determined that the introduction of rocks to the pile more influences a mixing of the pile than the actual discharging of the rocks from the pile. During discharging, it was evident that the “action” area of the pile resembled a plug flow system. The higher general Peclet numbers prove that the system as whole tends to operation as a plug flow; this is especially evident when outliers, or the particles which separated from the general center of the pile during conveyor loading, were removed. While mean residence times were useful in understanding the general residence time within each pile, they were not very useful in generating an overall understanding of retention within the stockpile.

Results obtained from Chapter 4 prove information collected from aggregate stockpile simulations prepared using PFC3d are capable of mapping particle flow consistent with actual discharging rock stockpiles. Theoretically, the simulations provided accurate results consistent with how stockpile are expected to react during discharge. In addition to accurate results, the graphs prove the consistency of the simulations and the reliability of the PFC3D program. While this data cannot directly be used to predict residence time within a stockpile or the likelihood of arching within a stockpile, it does prove that PFC3D is capable of providing accurate flow representations of discharging stockpiled material. Velocity results obtained from simulations show results consistent with actual field results, as well as the ability for the simulations to show issues regarding arching and other potential safety issues.

Collectively, Chapters 3 and 4 provide information essential in obtaining a better understanding on how stockpiles discharge. Both proved that the area directly above the discharge point known as the “active” area tends to travel through the pile quicker than other areas and thus as a plug flow system. In addition, it should be noted that additional RTD analyses would allow for a better simulation to be developed.

While much of this information is useful, there is much more research that could be completed in order to obtain even more valuable data. As far as field, RTD, analyses it is suggested that future physical flow research perform a larger number of RTD analyses in order to develop a correlation between loading and discharge features. In addition, future research should perform residence time distribution analyses on various different starting locations on the pile. This information could lead to the development of rate equations based on stockpile height, or volume. Future modeling and simulation research should include particles more accurately shaped along with a discharge point settings which operate similar to that of an actual stockpile discharge feeder. Combining these points into a simulation while also being able to collect empirical data from a stockpile similar in size and design will allow for a direct comparison to be made, possibly resulting in equations capable of predicting both flow and safety issues which may be encountered while discharging from stockpiles of any shape. Increasing the number of analyses and tuning the simulations to be more realistic to actual stockpiles has the capability to provide a model capable of predicting flow information no matter where the particles location is within the pile. Obtaining this type of information could revolutionize stockpiling and could even save lives.

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Appendix A

Table A1 - RTD Analysis 1 – Rock Discharge Results

Rock Number	Large Rocks Camera Time	Large Rocks Monitored Time	Small Rocks Camera Time	Small Rocks Monitored Time
1	7:14	9:27	7:10	9:23
2	7:19	9:32	7:18	9:31
3	7:27	9:40	7:20	9:33
4	7:31	9:44	7:34	9:47
5	7:33	9:46	7:36	9:49
6	7:43	9:56	7:44	9:57
7	7:47	10:00	7:48	10:01
8	8:08	10:21	7:53	10:06
9	8:10	10:23	8:00	10:13
10	8:12	10:25	8:06	10:19
11	8:15	10:28	8:06	10:19
12	8:16	10:29	8:11	10:24
13	8:18	10:31	8:11	10:24
14	8:19	10:32	8:26	10:39
15	8:23	10:36	8:27	10:40
16	8:24	10:37	8:36	10:49
17	8:24	10:37	8:47	11:00
18	8:27	10:40	9:11	11:24
19	8:41	10:54	9:51	12:04
20	8:47	11:00	10:00	12:13
21	8:48	11:01		
22	9:08	11:21		
23	9:15	11:28		
24	9:16	11:29		
25	9:44	11:57		

Table A2 - RTD Analysis 2 – Rock Discharge Results

Rock Number	Large Rocks Camera Time	Large Rocks Monitored Time	Small Rocks Camera Time	Small Rocks Monitored Time
1	2:36:24	0:15:17	2:37:56	0:16:49
2	2:36:25	0:15:18	2:38:05	0:16:58
3	2:36:39	0:15:32	2:38:34	0:17:27
4	2:36:43	0:15:36	2:38:35	0:17:28
5	2:36:47	0:15:40	2:38:40	0:17:33
6	2:37:50	0:16:43	2:38:41	0:17:34
7	2:38:00	0:16:53	2:38:55	0:17:48
8	2:38:25	0:17:18	2:39:35	0:18:28
9	2:38:48	0:17:41	2:39:43	0:18:36
10	2:38:52	0:17:45	2:40:06	0:18:59
11	2:39:21	0:18:14	2:40:21	0:19:14
12	2:39:46	0:18:39	2:41:47	0:20:40
13	2:40:29	0:19:22	2:43:03	0:21:56
14	2:40:39	0:19:32	2:44:57	0:23:50
15	2:40:47	0:19:40	2:45:24	0:24:17
16	2:40:51	0:19:44	2:45:41	0:24:34
17	2:40:57	0:19:50	2:46:58	0:25:51
18	2:41:07	0:20:00	2:48:03	0:26:56
19	2:41:10	0:20:03	2:48:48	0:27:41
20	2:41:50	0:20:43	2:55:05	0:33:58
21	2:42:16	0:21:09	2:55:49	0:34:42
22	2:42:18	0:21:11	2:57:02	0:35:55
23	2:44:42	0:23:35	2:57:47	0:36:40
24	2:48:58	0:27:51	3:06:16	0:45:09
25	2:56:26	0:35:19		

Table A3 - RTD Analysis 3 – Rock Discharge Results

Rock Number	Large Rocks Camera Time	Large Rocks Monitored Time	Small Rocks Camera Time	Small Rocks Monitored Time
1	1:28:41	0:18:07	1:27:14	0:16:40
2	1:29:12	0:18:38	1:28:14	0:17:40
3	1:29:20	0:18:46	1:29:08	0:18:34
4	1:29:40	0:19:06	1:29:36	0:19:02
5	1:30:13	0:19:39	1:30:08	0:19:34
6	1:30:27	0:19:53	1:30:28	0:19:54
7	1:30:31	0:19:57	1:30:33	0:19:59
8	1:30:33	0:19:59	1:30:36	0:20:02
9	1:30:42	0:20:08	1:30:44	0:20:10
10	1:30:58	0:20:24	1:30:44	0:20:10
11	1:31:17	0:20:43	1:30:49	0:20:15
12	1:31:27	0:20:53	1:31:02	0:20:28
13	1:31:29	0:20:55	1:31:13	0:20:39
14	1:32:06	0:21:32	1:31:19	0:20:45
15	1:32:16	0:21:42	1:31:27	0:20:53
16	1:32:21	0:21:47	1:31:30	0:20:56
17	1:34:30	0:23:56	1:31:57	0:21:23
18	1:34:55	0:24:21	1:32:50	0:22:16
19	1:35:38	0:25:04	1:32:54	0:22:20
20	1:35:48	0:25:14	1:33:13	0:22:39
21	1:36:33	0:25:59	1:35:51	0:25:17
22	1:37:18	0:26:44	1:47:03	0:36:29
23	1:39:30	0:28:56	1:52:58	0:42:24
24	1:42:13	0:31:39		
25	2:07:12	0:56:38		

Appendix B

10 Meter Pile – 2.0 Discharge Opening

```
;fname: briansPFC10-2.DAT
; Height=10
new
; -----
def make_walls ; create walls: 5 plate floor
  wall_kn= 1e10

command
  wall id=6 type cylinder end1 0 0 -1 end2 0 0 10 rad 12.91 kn=wall_kn
end_command

command
  wall id=7 type cylinder end1 0 0 -2 end2 0 0 -14 rad 14.0 14.0 kn=wall_kn
end_command

  _x0 = 15
  _y0 = 15
  _z0 = -14
  _x1 = -15
  _y1 = 15
  _z1 = -14
  _x2 = -15
  _y2 = -15
  _z2 = -14
  _x3 = 15
  _y3 = -15
  _z3 = -14
command
  wall id=8 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) (_x3,_y3,_z3)
end_command

  _x0 = 15
  _y0 = 15
  _z0 = 0
  _x1 = -15
  _y1 = 15
  _z1 = 0
  _x2 = -15
  _y2 = 1
  _z2 = 0
  _x3 = 15
  _y3 = 1
```

```
_z3 = 0
command
  wall id=1 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command
```

```
_x0 = -1
_y0 = 2
_z0 = 0
_x1 = -15
_y1 = 2
_z1 = 0
_x2 = -15
_y2 = -2
_z2 = 0
_x3 = -1
_y3 = -2
_z3 = 0
```

```
command
  wall id=2 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command
```

```
_x0 = 15
_y0 = -1
_z0 = 0
_x1 = -15
_y1 = -1
_z1 = 0
_x2 = -15
_y2 = -15
_z2 = 0
_x3 = 15
_y3 = -15
_z3 = 0
```

```
command
  wall id=3 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command
```

```
_x0 = 15
_y0 = 2
_z0 = 0
_x1 = 1
_y1 = 2
_z1 = 0
_x2 = 1
_y2 = -2
```

```

_z2 = 0
_x3 = 15
_y3 = -2
_z3 = 0
command
  wall id=4 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

_x0 = 2
_y0 = 2
_z0 = 0
_x1 = -2
_y1 = 2
_z1 = 0
_x2 = -2
_y2 = -2
_z2 = 0
_x3 = 2
_y3 = -2
_z3 = 0
command
  wall id=5 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

end
; -----
def particle_create
  s_stiff=0.0 ; initial stiffnesses
  n_stiff=1e6
  tot_vol = (1.0/3.0)* pi * (rad^2.0) * height
  rbar   = 0.5 * (rlo + rhi)
  num    = int((1.0 - poros) * tot_vol / (4.0 / 3.0 * pi * rbar^3))
  mult   = 1.6 ; initial radius multiplication factor
  rlo_0  = rlo / mult
  rhi_0  = rhi / mult
command
  gen id=1,num rad=rlo_0,rhi_0 x=-11.736,11.736 y=-11.736,11.736 z=0.0,height &
    filter ff_outlet tries 3000000
  prop dens=500 ks=s_stiff kn=n_stiff
end_command
ii = out(string(num)+' particles were created')
sum = 0.0 ; get actual porosity
bp = ball_head
loop while bp # null
  sum = sum + 4.0 / 3.0 * pi * b_rad(bp)^3
  bp = b_next(bp)

```

```

end_loop
pmeas = 1.0 - sum / tot_vol
mult = ((1.0 - poros) / (1.0 - pmeas))^(1.0/3.0)
command
  ini rad mul mult
;   cycle 1000 =====
;   prop ks=0.5e6 fric 0.4 =====
  prop ks=0.5e6 fric 1000
end_command
end
;-----
def ff_outlet
  ff_outlet = 0
  _brad = fc_arg(0)
  _bx = fc_arg(1)
  _by = fc_arg(2)
  _bz = fc_arg(3)
  _rad = sqrt(_bx^2 + _by^2)
  if (_rad + _brad) > abs(((10 - (_bz + _brad)) / tan(.2222*pi))) then
    ff_outlet = 1
  end_if
end
;-----
macro zero 'ini xvel 0 yvel 0 zvel 0 xspin 0 yspin 0 zspin 0'
SET height=10 rad=11.73 rlo=0.1 rhi=.35 poros=0.40

make_walls
particle_create
plot create assembly
plot set cap size 25
plot set mag 1.5
plot set rot 0 0 40
plot add ball lorange

pl add wa wire on

pl sh

pause
save example_1-1-brian.SAV
;-----
; restore example_1-1-brian.sav
;-----
; HISTORY
;-----
;
;
history b xp 0 0 10.00 ;id=1
history b yp 0 0 10.00 ;id=2

```

```

history b zp 0 0 10.00 ;id=3
history b xv 0 0 10.00 ;id=4
history b yv 0 0 10.00 ;id=5
history b zv 0 0 10.00 ;id=6
;
history b xp 0.234 0 9.80 ;id=7
history b yp 0.234 0 9.80 ;id=8
history b zp 0.234 0 9.80 ;id=9
history b xv 0.234 0 9.80 ;id=10
history b yv 0.234 0 9.80 ;id=11
history b zv 0.234 0 9.80 ;id=12
;
history b xp -0.234 0 9.80 ;id=13
history b yp -0.234 0 9.80 ;id=14
history b zp -0.234 0 9.80 ;id=15
history b xv -0.234 0 9.80 ;id=16
history b yv -0.234 0 9.80 ;id=17
history b zv -0.234 0 9.80 ;id=18
;
history b xp 0 0.234 9.80 ;id=19
history b yp 0 0.234 9.80 ;id=20
history b zp 0 0.234 9.80 ;id=21
history b xv 0 0.234 9.80 ;id=22
history b yv 0 0.234 9.80 ;id=23
history b zv 0 0.234 9.80 ;id=24
;
history b xp 0 -0.234 9.80 ;id=25
history b yp 0 -0.234 9.80 ;id=26
history b zp 0 -0.234 9.80 ;id=27
history b xv 0 -0.234 9.80 ;id=28
history b yv 0 -0.234 9.80 ;id=29
history b zv 0 -0.234 9.80 ;id=30
;
history b xp 0.469 0 9.60 ;id=31
history b yp 0.469 0 9.60 ;id=32
history b zp 0.469 0 9.60 ;id=33
history b xv 0.469 0 9.60 ;id=34
history b yv 0.469 0 9.60 ;id=35
history b zv 0.469 0 9.60 ;id=36
;
history b xp -0.469 0 9.60 ;id=37
history b yp -0.469 0 9.60 ;id=38
history b zp -0.469 0 9.60 ;id=39
history b xv -0.469 0 9.60 ;id=40
history b yv -0.469 0 9.60 ;id=41
history b zv -0.469 0 9.60 ;id=42
;
history b xp 0 0.469 9.60 ;id=43

```

```

history b yp 0 0.469 9.60 ;id=44
history b zp 0 0.469 9.60 ;id=45
history b xv 0 0.469 9.60 ;id=46
history b yv 0 0.469 9.60 ;id=47
history b zv 0 0.469 9.60 ;id=48
;
history b xp 0 -0.469 9.60 ;id=49
history b yp 0 -0.469 9.60 ;id=50
history b zp 0 -0.469 9.60 ;id=51
history b xv 0 -0.469 9.60 ;id=52
history b yv 0 -0.469 9.60 ;id=53
history b zv 0 -0.469 9.60 ;id=54
;
history b xp 0.704 0 9.40 ;id=55
history b yp 0.704 0 9.40 ;id=56
history b zp 0.704 0 9.40 ;id=57
history b xv 0.704 0 9.40 ;id=58
history b yv 0.704 0 9.40 ;id=59
history b zv 0.704 0 9.40 ;id=60
;
history b xp -0.704 0 9.40 ;id=61
history b yp -0.704 0 9.40 ;id=62
history b zp -0.704 0 9.40 ;id=63
history b xv -0.704 0 9.40 ;id=64
history b yv -0.704 0 9.40 ;id=65
history b zv -0.704 0 9.40 ;id=66
;
history b xp 0 0.704 9.40 ;id=67
history b yp 0 0.704 9.40 ;id=68
history b zp 0 0.704 9.40 ;id=69
history b xv 0 0.704 9.40 ;id=70
history b yv 0 0.704 9.40 ;id=71
history b zv 0 0.704 9.40 ;id=72
;
history b xp 0 -0.704 9.40 ;id=73
history b yp 0 -0.704 9.40 ;id=74
history b zp 0 -0.704 9.40 ;id=75
history b xv 0 -0.704 9.40 ;id=76
history b yv 0 -0.704 9.40 ;id=77
history b zv 0 -0.704 9.40 ;id=78
;
history b xp 0.938 0 9.20 ;id=79
history b yp 0.938 0 9.20 ;id=80
history b zp 0.938 0 9.20 ;id=81
history b xv 0.938 0 9.20 ;id=82
history b yv 0.938 0 9.20 ;id=83
history b zv 0.938 0 9.20 ;id=84
;

```

```

history b xp -0.938 0 9.20 ;id=85
history b yp -0.938 0 9.20 ;id=86
history b zp -0.938 0 9.20 ;id=87
history b xv -0.938 0 9.20 ;id=88
history b yv -0.938 0 9.20 ;id=89
history b zv -0.938 0 9.20 ;id=90
;
history b xp 0 0.938 9.20 ;id=91
history b yp 0 0.938 9.20 ;id=92
history b zp 0 0.938 9.20 ;id=93
history b xv 0 0.938 9.20 ;id=94
history b yv 0 0.938 9.20 ;id=95
history b zv 0 0.938 9.20 ;id=96
;
history b xp 0 -0.938 9.20 ;id=97
history b yp 0 -0.938 9.20 ;id=98
history b zp 0 -0.938 9.20 ;id=99
history b xv 0 -0.938 9.20 ;id=100
history b yv 0 -0.938 9.20 ;id=101
history b zv 0 -0.938 9.20 ;id=102
;
history b xp 1.17 0 9.00 ;id=103
history b yp 1.17 0 9.00 ;id=104
history b zp 1.17 0 9.00 ;id=105
history b xv 1.17 0 9.00 ;id=106
history b yv 1.17 0 9.00 ;id=107
history b zv 1.17 0 9.00 ;id=108
;
history b xp -1.17 0 9.00 ;id=109
history b yp -1.17 0 9.00 ;id=110
history b zp -1.17 0 9.00 ;id=111
history b xv -1.17 0 9.00 ;id=112
history b yv -1.17 0 9.00 ;id=113
history b zv -1.17 0 9.00 ;id=114
;
history b xp 0 1.17 9.00 ;id=115
history b yp 0 1.17 9.00 ;id=116
history b zp 0 1.17 9.00 ;id=117
history b xv 0 1.17 9.00 ;id=118
history b yv 0 1.17 9.00 ;id=119
history b zv 0 1.17 9.00 ;id=120
;
history b xp 0 -1.17 9.00 ;id=121
history b yp 0 -1.17 9.00 ;id=122
history b zp 0 -1.17 9.00 ;id=123
history b xv 0 -1.17 9.00 ;id=124
history b yv 0 -1.17 9.00 ;id=125
history b zv 0 -1.17 9.00 ;id=126

```

```

;
history b xp 2.34 0 8.00 ;id=127
history b yp 2.34 0 8.00 ;id=128
history b zp 2.34 0 8.00 ;id=129
history b xv 2.34 0 8.00 ;id=130
history b yv 2.34 0 8.00 ;id=131
history b zv 2.34 0 8.00 ;id=132
;
history b xp -2.34 0 8.00 ;id=133
history b yp -2.34 0 8.00 ;id=134
history b zp -2.34 0 8.00 ;id=135
history b xv -2.34 0 8.00 ;id=136
history b yv -2.34 0 8.00 ;id=137
history b zv -2.34 0 8.00 ;id=138
;
history b xp 0 2.34 8.00 ;id=139
history b yp 0 2.34 8.00 ;id=140
history b zp 0 2.34 8.00 ;id=141
history b xv 0 2.34 8.00 ;id=142
history b yv 0 2.34 8.00 ;id=143
history b zv 0 2.34 8.00 ;id=144
;
history b xp 0 -2.34 8.00 ;id=145
history b yp 0 -2.34 8.00 ;id=146
history b zp 0 -2.34 8.00 ;id=147
history b xv 0 -2.34 8.00 ;id=148
history b yv 0 -2.34 8.00 ;id=149
history b zv 0 -2.34 8.00 ;id=150
;
history b xp 3.52 0 7.00 ;id=151
history b yp 3.52 0 7.00 ;id=152
history b zp 3.52 0 7.00 ;id=153
history b xv 3.52 0 7.00 ;id=154
history b yv 3.52 0 7.00 ;id=155
history b zv 3.52 0 7.00 ;id=156
;
history b xp -3.52 0 7.00 ;id=157
history b yp -3.52 0 7.00 ;id=158
history b zp -3.52 0 7.00 ;id=159
history b xv -3.52 0 7.00 ;id=160
history b yv -3.52 0 7.00 ;id=161
history b zv -3.52 0 7.00 ;id=162
;
history b xp 0 3.52 7.00 ;id=163
history b yp 0 3.52 7.00 ;id=164
history b zp 0 3.52 7.00 ;id=165
history b xv 0 3.52 7.00 ;id=166
history b yv 0 3.52 7.00 ;id=167

```

```

history b zv 0 3.52 7.00 ;id=168
;
history b xp 0 -3.52 7.00 ;id=169
history b yp 0 -3.52 7.00 ;id=170
history b zp 0 -3.52 7.00 ;id=171
history b xv 0 -3.52 7.00 ;id=172
history b yv 0 -3.52 7.00 ;id=173
history b zv 0 -3.52 7.00 ;id=174
;
history b xp 4.69 0 6.00 ;id=175
history b yp 4.69 0 6.00 ;id=176
history b zp 4.69 0 6.00 ;id=177
history b xv 4.69 0 6.00 ;id=178
history b yv 4.69 0 6.00 ;id=179
history b zv 4.69 0 6.00 ;id=180
;
history b xp -4.69 0 6.00 ;id=181
history b yp -4.69 0 6.00 ;id=182
history b zp -4.69 0 6.00 ;id=183
history b xv -4.69 0 6.00 ;id=184
history b yv -4.69 0 6.00 ;id=185
history b zv -4.69 0 6.00 ;id=186
;
history b xp 0 4.69 6.00 ;id=187
history b yp 0 4.69 6.00 ;id=188
history b zp 0 4.69 6.00 ;id=189
history b xv 0 4.69 6.00 ;id=190
history b yv 0 4.69 6.00 ;id=191
history b zv 0 4.69 6.00 ;id=192
;
history b xp 0 -4.69 6.00 ;id=193
history b yp 0 -4.69 6.00 ;id=194
history b zp 0 -4.69 6.00 ;id=195
history b xv 0 -4.69 6.00 ;id=196
history b yv 0 -4.69 6.00 ;id=197
history b zv 0 -4.69 6.00 ;id=198
;
history b xp 5.86 0 5.00 ;id=199
history b yp 5.86 0 5.00 ;id=200
history b zp 5.86 0 5.00 ;id=201
history b xv 5.86 0 5.00 ;id=202
history b yv 5.86 0 5.00 ;id=203
history b zv 5.86 0 5.00 ;id=204
;
history b xp -5.86 0 5.00 ;id=205
history b yp -5.86 0 5.00 ;id=206
history b zp -5.86 0 5.00 ;id=207
history b xv -5.86 0 5.00 ;id=208

```

```

history b yv -5.86 0 5.00 ;id=209
history b zv -5.86 0 5.00 ;id=210
;
history b xp 0 5.86 5.00 ;id=211
history b yp 0 5.86 5.00 ;id=212
history b zp 0 5.86 5.00 ;id=213
history b xv 0 5.86 5.00 ;id=214
history b yv 0 5.86 5.00 ;id=215
history b zv 0 5.86 5.00 ;id=216
;
history b xp 0 -5.86 5.00 ;id=217
history b yp 0 -5.86 5.00 ;id=218
history b zp 0 -5.86 5.00 ;id=219
history b xv 0 -5.86 5.00 ;id=220
history b yv 0 -5.86 5.00 ;id=221
history b zv 0 -5.86 5.00 ;id=222
;
history b xp 6.45 0 4.50 ;id=223
history b yp 6.45 0 4.50 ;id=224
history b zp 6.45 0 4.50 ;id=225
history b xv 6.45 0 4.50 ;id=226
history b yv 6.45 0 4.50 ;id=227
history b zv 6.45 0 4.50 ;id=228
;
history b xp -6.45 0 4.50 ;id=229
history b yp -6.45 0 4.50 ;id=230
history b zp -6.45 0 4.50 ;id=231
history b xv -6.45 0 4.50 ;id=232
history b yv -6.45 0 4.50 ;id=233
history b zv -6.45 0 4.50 ;id=234
;
history b xp 0 6.45 4.50 ;id=235
history b yp 0 6.45 4.50 ;id=236
history b zp 0 6.45 4.50 ;id=237
history b xv 0 6.45 4.50 ;id=238
history b yv 0 6.45 4.50 ;id=239
history b zv 0 6.45 4.50 ;id=240
;
history b xp 0 -6.45 4.50 ;id=241
history b yp 0 -6.45 4.50 ;id=242
history b zp 0 -6.45 4.50 ;id=243
history b xv 0 -6.45 4.50 ;id=244
history b yv 0 -6.45 4.50 ;id=245
history b zv 0 -6.45 4.50 ;id=246
;
;-----

```

```

; delete wall 5 ; ++++++ switch order of grav wall delete =====

```

```
; set gravity 0 0 -9.81
; cycle 5000
```

```
his dia muf ; =====
```

```
set grav 0 0 -9.81; =====
```

```
cy 3000
```

```
save grav1.sav; =====
```

```
del wa 5; =====
```

```
cy 5000; =====
```

```
; -----
```

```
save brian10-2-1.sav
```

```
cycle 50000
```

```
save brian10-2-2.sav
```

```
cycle 50000
```

```
save brian10-2-3.sav
```

```
cycle 50000
```

```
save brian10-2-4.sav
```

```
cycle 50000
```

```
save brian10-2-5.sav
```

```
cycle 50000
```

```
save brian10-2-6.sav
```

```
cycle 50000
```

```
save brian10-2-7.sav
```

```
cycle 50000
```

```
save brian10-2-8.sav
```

```
cycle 50000
```

```
save brian10-2-9.sav
```

```
cycle 50000
```

```
save brian10-2-10.sav
```

```
cycle 50000
```

```
save brian10-2-11.sav
```

```
cycle 50000
```

```
save brian10-2-12.sav
```

```
cycle 50000  
save brian10-2-13.sav
```

```
; -----
```

```
; -----
```

```
pl sh
```

10 Meter Pile – 2.5 Discharge Opening

```
;fname: briansPFC10-2.5.DAT
; Height=10
new
; -----
def make_walls ; create walls: 5 plate floor
  wall_kn= 1e10

command
  wall id=6 type cylinder end1 0 0 -1 end2 0 0 10 rad 12.91 kn=wall_kn
end_command

command
  wall id=7 type cylinder end1 0 0 -2 end2 0 0 -14 rad 14.0 14.0 kn=wall_kn
end_command

  _x0 = 15
  _y0 = 15
  _z0 = -14
  _x1 = -15
  _y1 = 15
  _z1 = -14
  _x2 = -15
  _y2 = -15
  _z2 = -14
  _x3 = 15
  _y3 = -15
  _z3 = -14
command
  wall id=8 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) (_x3,_y3,_z3)
end_command

  _x0 = 15
  _y0 = 15
  _z0 = 0
  _x1 = -15
  _y1 = 15
  _z1 = 0
  _x2 = -15
  _y2 = 1.25
  _z2 = 0
  _x3 = 15
  _y3 = 1.25
  _z3 = 0
command
  wall id=1 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
```

```
end_command
```

```
_x0 = -1.25  
_y0 = 2  
_z0 = 0  
_x1 = -15  
_y1 = 2  
_z1 = 0  
_x2 = -15  
_y2 = -2  
_z2 = 0  
_x3 = -1.25  
_y3 = -2  
_z3 = 0
```

```
command
```

```
wall id=2 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &  
  (_x3,_y3,_z3)  
end_command
```

```
_x0 = 15  
_y0 = -1.25  
_z0 = 0  
_x1 = -15  
_y1 = -1.25  
_z1 = 0  
_x2 = -15  
_y2 = -15  
_z2 = 0  
_x3 = 15  
_y3 = -15  
_z3 = 0
```

```
command
```

```
wall id=3 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &  
  (_x3,_y3,_z3)  
end_command
```

```
_x0 = 15  
_y0 = 2  
_z0 = 0  
_x1 = 1.25  
_y1 = 2  
_z1 = 0  
_x2 = 1.25  
_y2 = -2  
_z2 = 0  
_x3 = 15  
_y3 = -2  
_z3 = 0
```

```

command
  wall id=4 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

```

_x0 = 2
_y0 = 2
_z0 = 0
_x1 = -2
_y1 = 2
_z1 = 0
_x2 = -2
_y2 = -2
_z2 = 0
_x3 = 2
_y3 = -2
_z3 = 0

```

```

command
  wall id=5 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

```
end
```

```
;-----
```

```

def particle_create
  s_stiff=0.0 ; initial stiffnesses
  n_stiff=1e6
  tot_vol = (1.0/3.0)* pi * (rad^2.0) * height
  rbar = 0.5 * (rlo + rhi)
  num = int((1.0 - poros) * tot_vol / (4.0 / 3.0 * pi * rbar^3))
  mult = 1.6 ; initial radius multiplication factor
  rlo_0 = rlo / mult
  rhi_0 = rhi / mult
  command
    gen id=1,num rad=rlo_0,rhi_0 x=-11.736,11.736 y=-11.736,11.736 z=0.0,height &
      filter ff_outlet tries 3000000
    prop dens=500 ks=s_stiff kn=n_stiff
  end_command
  ii = out(string(num)+' particles were created')
  sum = 0.0 ; get actual porosity
  bp = ball_head
  loop while bp # null
    sum = sum + 4.0 / 3.0 * pi * b_rad(bp)^3
    bp = b_next(bp)
  end_loop
  pmeas = 1.0 - sum / tot_vol
  mult = ((1.0 - poros) / (1.0 - pmeas))^(1.0/3.0)
  command

```

```

ini rad mul mult
; cycle 1000 =====
; prop ks=0.5e6 fric 0.4 =====
prop ks=0.5e6 fric 1000
end_command
end
; -----
def ff_outlet
ff_outlet = 0
_brad = fc_arg(0)
_bx = fc_arg(1)
_by = fc_arg(2)
_bz = fc_arg(3)
_rad = sqrt(_bx^2 + _by^2)
if (_rad + _brad) > abs(((10 - (_bz + _brad)) / tan(.2222*pi))) then
ff_outlet = 1
end_if
end
; -----
macro zero 'ini xvel 0 yvel 0 zvel 0 xspin 0 yspin 0 zspin 0'
SET height=10 rad=11.73 rlo=0.1 rhi=.35 poros=0.40

make_walls
particle_create
plot create assembly
plot set cap size 25
plot set mag 1.5
plot set rot 0 0 40
plot add ball lorange

pl add wa wire on

pl sh

pause
save example_1-1-brian.SAV
; -----
; restore example_1-1-brian.sav
; -----
; HISTORY
; -----
;
history b xp 0 0 10.00 ;id=1
history b yp 0 0 10.00 ;id=2
history b zp 0 0 10.00 ;id=3
history b xv 0 0 10.00 ;id=4
history b yv 0 0 10.00 ;id=5
history b zv 0 0 10.00 ;id=6

```

```

;
history b xp 0.234 0 9.80 ;id=7
history b yp 0.234 0 9.80 ;id=8
history b zp 0.234 0 9.80 ;id=9
history b xv 0.234 0 9.80 ;id=10
history b yv 0.234 0 9.80 ;id=11
history b zv 0.234 0 9.80 ;id=12
;
history b xp -0.234 0 9.80 ;id=13
history b yp -0.234 0 9.80 ;id=14
history b zp -0.234 0 9.80 ;id=15
history b xv -0.234 0 9.80 ;id=16
history b yv -0.234 0 9.80 ;id=17
history b zv -0.234 0 9.80 ;id=18
;
history b xp 0 0.234 9.80 ;id=19
history b yp 0 0.234 9.80 ;id=20
history b zp 0 0.234 9.80 ;id=21
history b xv 0 0.234 9.80 ;id=22
history b yv 0 0.234 9.80 ;id=23
history b zv 0 0.234 9.80 ;id=24
;
history b xp 0 -0.234 9.80 ;id=25
history b yp 0 -0.234 9.80 ;id=26
history b zp 0 -0.234 9.80 ;id=27
history b xv 0 -0.234 9.80 ;id=28
history b yv 0 -0.234 9.80 ;id=29
history b zv 0 -0.234 9.80 ;id=30
;
history b xp 0.469 0 9.60 ;id=31
history b yp 0.469 0 9.60 ;id=32
history b zp 0.469 0 9.60 ;id=33
history b xv 0.469 0 9.60 ;id=34
history b yv 0.469 0 9.60 ;id=35
history b zv 0.469 0 9.60 ;id=36
;
history b xp -0.469 0 9.60 ;id=37
history b yp -0.469 0 9.60 ;id=38
history b zp -0.469 0 9.60 ;id=39
history b xv -0.469 0 9.60 ;id=40
history b yv -0.469 0 9.60 ;id=41
history b zv -0.469 0 9.60 ;id=42
;
history b xp 0 0.469 9.60 ;id=43
history b yp 0 0.469 9.60 ;id=44
history b zp 0 0.469 9.60 ;id=45
history b xv 0 0.469 9.60 ;id=46
history b yv 0 0.469 9.60 ;id=47

```

```

history b zv 0 0.469 9.60 ;id=48
;
history b xp 0 -0.469 9.60 ;id=49
history b yp 0 -0.469 9.60 ;id=50
history b zp 0 -0.469 9.60 ;id=51
history b xv 0 -0.469 9.60 ;id=52
history b yv 0 -0.469 9.60 ;id=53
history b zv 0 -0.469 9.60 ;id=54
;
history b xp 0.704 0 9.40 ;id=55
history b yp 0.704 0 9.40 ;id=56
history b zp 0.704 0 9.40 ;id=57
history b xv 0.704 0 9.40 ;id=58
history b yv 0.704 0 9.40 ;id=59
history b zv 0.704 0 9.40 ;id=60
;
history b xp -0.704 0 9.40 ;id=61
history b yp -0.704 0 9.40 ;id=62
history b zp -0.704 0 9.40 ;id=63
history b xv -0.704 0 9.40 ;id=64
history b yv -0.704 0 9.40 ;id=65
history b zv -0.704 0 9.40 ;id=66
;
history b xp 0 0.704 9.40 ;id=67
history b yp 0 0.704 9.40 ;id=68
history b zp 0 0.704 9.40 ;id=69
history b xv 0 0.704 9.40 ;id=70
history b yv 0 0.704 9.40 ;id=71
history b zv 0 0.704 9.40 ;id=72
;
history b xp 0 -0.704 9.40 ;id=73
history b yp 0 -0.704 9.40 ;id=74
history b zp 0 -0.704 9.40 ;id=75
history b xv 0 -0.704 9.40 ;id=76
history b yv 0 -0.704 9.40 ;id=77
history b zv 0 -0.704 9.40 ;id=78
;
history b xp 0.938 0 9.20 ;id=79
history b yp 0.938 0 9.20 ;id=80
history b zp 0.938 0 9.20 ;id=81
history b xv 0.938 0 9.20 ;id=82
history b yv 0.938 0 9.20 ;id=83
history b zv 0.938 0 9.20 ;id=84
;
history b xp -0.938 0 9.20 ;id=85
history b yp -0.938 0 9.20 ;id=86
history b zp -0.938 0 9.20 ;id=87
history b xv -0.938 0 9.20 ;id=88

```

```

history b yv -0.938 0 9.20 ;id=89
history b zv -0.938 0 9.20 ;id=90
;
history b xp 0 0.938 9.20 ;id=91
history b yp 0 0.938 9.20 ;id=92
history b zp 0 0.938 9.20 ;id=93
history b xv 0 0.938 9.20 ;id=94
history b yv 0 0.938 9.20 ;id=95
history b zv 0 0.938 9.20 ;id=96
;
history b xp 0 -0.938 9.20 ;id=97
history b yp 0 -0.938 9.20 ;id=98
history b zp 0 -0.938 9.20 ;id=99
history b xv 0 -0.938 9.20 ;id=100
history b yv 0 -0.938 9.20 ;id=101
history b zv 0 -0.938 9.20 ;id=102
;
history b xp 1.17 0 9.00 ;id=103
history b yp 1.17 0 9.00 ;id=104
history b zp 1.17 0 9.00 ;id=105
history b xv 1.17 0 9.00 ;id=106
history b yv 1.17 0 9.00 ;id=107
history b zv 1.17 0 9.00 ;id=108
;
history b xp -1.17 0 9.00 ;id=109
history b yp -1.17 0 9.00 ;id=110
history b zp -1.17 0 9.00 ;id=111
history b xv -1.17 0 9.00 ;id=112
history b yv -1.17 0 9.00 ;id=113
history b zv -1.17 0 9.00 ;id=114
;
history b xp 0 1.17 9.00 ;id=115
history b yp 0 1.17 9.00 ;id=116
history b zp 0 1.17 9.00 ;id=117
history b xv 0 1.17 9.00 ;id=118
history b yv 0 1.17 9.00 ;id=119
history b zv 0 1.17 9.00 ;id=120
;
history b xp 0 -1.17 9.00 ;id=121
history b yp 0 -1.17 9.00 ;id=122
history b zp 0 -1.17 9.00 ;id=123
history b xv 0 -1.17 9.00 ;id=124
history b yv 0 -1.17 9.00 ;id=125
history b zv 0 -1.17 9.00 ;id=126
;
history b xp 2.34 0 8.00 ;id=127
history b yp 2.34 0 8.00 ;id=128
history b zp 2.34 0 8.00 ;id=129

```

```

history b xv 2.34 0 8.00 ;id=130
history b yv 2.34 0 8.00 ;id=131
history b zv 2.34 0 8.00 ;id=132
;
history b xp -2.34 0 8.00 ;id=133
history b yp -2.34 0 8.00 ;id=134
history b zp -2.34 0 8.00 ;id=135
history b xv -2.34 0 8.00 ;id=136
history b yv -2.34 0 8.00 ;id=137
history b zv -2.34 0 8.00 ;id=138
;
history b xp 0 2.34 8.00 ;id=139
history b yp 0 2.34 8.00 ;id=140
history b zp 0 2.34 8.00 ;id=141
history b xv 0 2.34 8.00 ;id=142
history b yv 0 2.34 8.00 ;id=143
history b zv 0 2.34 8.00 ;id=144
;
history b xp 0 -2.34 8.00 ;id=145
history b yp 0 -2.34 8.00 ;id=146
history b zp 0 -2.34 8.00 ;id=147
history b xv 0 -2.34 8.00 ;id=148
history b yv 0 -2.34 8.00 ;id=149
history b zv 0 -2.34 8.00 ;id=150
;
history b xp 3.52 0 7.00 ;id=151
history b yp 3.52 0 7.00 ;id=152
history b zp 3.52 0 7.00 ;id=153
history b xv 3.52 0 7.00 ;id=154
history b yv 3.52 0 7.00 ;id=155
history b zv 3.52 0 7.00 ;id=156
;
history b xp -3.52 0 7.00 ;id=157
history b yp -3.52 0 7.00 ;id=158
history b zp -3.52 0 7.00 ;id=159
history b xv -3.52 0 7.00 ;id=160
history b yv -3.52 0 7.00 ;id=161
history b zv -3.52 0 7.00 ;id=162
;
history b xp 0 3.52 7.00 ;id=163
history b yp 0 3.52 7.00 ;id=164
history b zp 0 3.52 7.00 ;id=165
history b xv 0 3.52 7.00 ;id=166
history b yv 0 3.52 7.00 ;id=167
history b zv 0 3.52 7.00 ;id=168
;
history b xp 0 -3.52 7.00 ;id=169
history b yp 0 -3.52 7.00 ;id=170

```

```

history b zp 0 -3.52 7.00 ;id=171
history b xv 0 -3.52 7.00 ;id=172
history b yv 0 -3.52 7.00 ;id=173
history b zv 0 -3.52 7.00 ;id=174
;
history b xp 4.69 0 6.00 ;id=175
history b yp 4.69 0 6.00 ;id=176
history b zp 4.69 0 6.00 ;id=177
history b xv 4.69 0 6.00 ;id=178
history b yv 4.69 0 6.00 ;id=179
history b zv 4.69 0 6.00 ;id=180
;
history b xp -4.69 0 6.00 ;id=181
history b yp -4.69 0 6.00 ;id=182
history b zp -4.69 0 6.00 ;id=183
history b xv -4.69 0 6.00 ;id=184
history b yv -4.69 0 6.00 ;id=185
history b zv -4.69 0 6.00 ;id=186
;
history b xp 0 4.69 6.00 ;id=187
history b yp 0 4.69 6.00 ;id=188
history b zp 0 4.69 6.00 ;id=189
history b xv 0 4.69 6.00 ;id=190
history b yv 0 4.69 6.00 ;id=191
history b zv 0 4.69 6.00 ;id=192
;
history b xp 0 -4.69 6.00 ;id=193
history b yp 0 -4.69 6.00 ;id=194
history b zp 0 -4.69 6.00 ;id=195
history b xv 0 -4.69 6.00 ;id=196
history b yv 0 -4.69 6.00 ;id=197
history b zv 0 -4.69 6.00 ;id=198
;
history b xp 5.86 0 5.00 ;id=199
history b yp 5.86 0 5.00 ;id=200
history b zp 5.86 0 5.00 ;id=201
history b xv 5.86 0 5.00 ;id=202
history b yv 5.86 0 5.00 ;id=203
history b zv 5.86 0 5.00 ;id=204
;
history b xp -5.86 0 5.00 ;id=205
history b yp -5.86 0 5.00 ;id=206
history b zp -5.86 0 5.00 ;id=207
history b xv -5.86 0 5.00 ;id=208
history b yv -5.86 0 5.00 ;id=209
history b zv -5.86 0 5.00 ;id=210
;
history b xp 0 5.86 5.00 ;id=211

```

```

history b yp 0 5.86 5.00 ;id=212
history b zp 0 5.86 5.00 ;id=213
history b xv 0 5.86 5.00 ;id=214
history b yv 0 5.86 5.00 ;id=215
history b zv 0 5.86 5.00 ;id=216
;
history b xp 0 -5.86 5.00 ;id=217
history b yp 0 -5.86 5.00 ;id=218
history b zp 0 -5.86 5.00 ;id=219
history b xv 0 -5.86 5.00 ;id=220
history b yv 0 -5.86 5.00 ;id=221
history b zv 0 -5.86 5.00 ;id=222
;
history b xp 6.45 0 4.50 ;id=223
history b yp 6.45 0 4.50 ;id=224
history b zp 6.45 0 4.50 ;id=225
history b xv 6.45 0 4.50 ;id=226
history b yv 6.45 0 4.50 ;id=227
history b zv 6.45 0 4.50 ;id=228
;
history b xp -6.45 0 4.50 ;id=229
history b yp -6.45 0 4.50 ;id=230
history b zp -6.45 0 4.50 ;id=231
history b xv -6.45 0 4.50 ;id=232
history b yv -6.45 0 4.50 ;id=233
history b zv -6.45 0 4.50 ;id=234
;
history b xp 0 6.45 4.50 ;id=235
history b yp 0 6.45 4.50 ;id=236
history b zp 0 6.45 4.50 ;id=237
history b xv 0 6.45 4.50 ;id=238
history b yv 0 6.45 4.50 ;id=239
history b zv 0 6.45 4.50 ;id=240
;
history b xp 0 -6.45 4.50 ;id=241
history b yp 0 -6.45 4.50 ;id=242
history b zp 0 -6.45 4.50 ;id=243
history b xv 0 -6.45 4.50 ;id=244
history b yv 0 -6.45 4.50 ;id=245
history b zv 0 -6.45 4.50 ;id=246
;
;-----

```

```

; delete wall 5 ;+++++++ switch order of grav wall delete =====
; set gravity 0 0 -9.81
; cycle 5000

```

```

his dia muf ;=====

```

```
set grav 0 0 -9.81; =====
```

```
cy 3000
```

```
save grav1.sav; =====
```

```
del wa 5; =====
```

```
cy 5000; =====
```

```
; -----
```

```
save brian10-2.5-1.sav
```

```
cycle 50000
```

```
save brian10-2.5-2.sav
```

```
cycle 50000
```

```
save brian10-2.5-3.sav
```

```
cycle 50000
```

```
save brian10-2.5-4.sav
```

```
cycle 50000
```

```
save brian10-2.5-5.sav
```

```
cycle 50000
```

```
save brian10-2.5-6.sav
```

```
cycle 50000
```

```
save brian10-2.5-7.sav
```

```
cycle 50000
```

```
save brian10-2.5-8.sav
```

```
cycle 50000
```

```
save brian10-2.5-9.sav
```

```
cycle 50000
```

```
save brian10-2.5-10.sav
```

```
cycle 50000
```

```
save brian10-2.5-11.sav
```

```
cycle 50000
```

```
save brian10-2.5-12.sav
```

```
cycle 50000
```

```
save brian10-2.5-13.sav
```

;

;

pl sh

12 Meter Pile – 2.0 Discharge Opening

```
;fname: briansPFC12-2.0.DAT
```

```
; Height=12
```

```
new
```

```
;-----
```

```
def make_walls ; create walls: 5 plate floor
```

```
  wall_kn= 1e10
```

```
command
```

```
  wall id=6 type cylinder end1 0 0 -1 end2 0 0 12 rad 15.4928 kn=wall_kn
```

```
end_command
```

```
command
```

```
  wall id=7 type cylinder end1 0 0 -2 end2 0 0 -14 rad 14.0 14.0 kn=wall_kn
```

```
end_command
```

```
  _x0 = 15
```

```
  _y0 = 15
```

```
  _z0 = -14
```

```
  _x1 = -15
```

```
  _y1 = 15
```

```
  _z1 = -14
```

```
  _x2 = -15
```

```
  _y2 = -15
```

```
  _z2 = -14
```

```
  _x3 = 15
```

```
  _y3 = -15
```

```
  _z3 = -14
```

```
command
```

```
  wall id=8 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) (_x3,_y3,_z3)
```

```
end_command
```

```
  _x0 = 15
```

```
  _y0 = 15
```

```
  _z0 = 0
```

```
  _x1 = -15
```

```
  _y1 = 15
```

```
  _z1 = 0
```

```
  _x2 = -15
```

```
  _y2 = 1
```

```
  _z2 = 0
```

```
  _x3 = 15
```

```
  _y3 = 1
```

```
  _z3 = 0
```

```
command
```

```
  wall id=1 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
```

```
  (_x3,_y3,_z3)
```

end_command

_x0 = -1
_y0 = 2
_z0 = 0
_x1 = -15
_y1 = 2
_z1 = 0
_x2 = -15
_y2 = -2
_z2 = 0
_x3 = -1
_y3 = -2
_z3 = 0

command

wall id=2 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
(_x3,_y3,_z3)
end_command

_x0 = 15
_y0 = -1
_z0 = 0
_x1 = -15
_y1 = -1
_z1 = 0
_x2 = -15
_y2 = -15
_z2 = 0
_x3 = 15
_y3 = -15
_z3 = 0

command

wall id=3 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
(_x3,_y3,_z3)
end_command

_x0 = 15
_y0 = 2
_z0 = 0
_x1 = 1
_y1 = 2
_z1 = 0
_x2 = 1
_y2 = -2
_z2 = 0
_x3 = 15
_y3 = -2
_z3 = 0

```

command
  wall id=4 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

```

_x0 = 2
_y0 = 2
_z0 = 0
_x1 = -2
_y1 = 2
_z1 = 0
_x2 = -2
_y2 = -2
_z2 = 0
_x3 = 2
_y3 = -2
_z3 = 0

```

```

command
  wall id=5 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

end

```

def particle_create
  s_stiff=0.0 ; initial stiffnesses
  n_stiff=1e6
  tot_vol = (1.0/3.0)* pi * (rad^2.0) * height
  rbar   = 0.5 * (rlo + rhi)
  num    = int((1.0 - poros) * tot_vol / (4.0 / 3.0 * pi * rbar^3))
  mult   = 1.6 ; initial radius multiplication factor
  rlo_0  = rlo / mult
  rhi_0  = rhi / mult
  command
    gen id=1,num rad=rlo_0,rhi_0 x=-14.301,14.301 y=-14.301,14.301 z=0.0,height &
      filter ff_outlet tries 3000000
    prop dens=500 ks=s_stiff kn=n_stiff
  end_command
  ii = out(string(num)+' particles were created')
  sum = 0.0 ; get actual porosity
  bp = ball_head
  loop while bp # null
    sum = sum + 4.0 / 3.0 * pi * b_rad(bp)^3
    bp = b_next(bp)
  end_loop
  pmeas = 1.0 - sum / tot_vol
  mult = ((1.0 - poros) / (1.0 - pmeas))^(1.0/3.0)
  command

```

```

ini rad mul mult
; cycle 1000 =====
; prop ks=0.5e6 fric 0.4 =====
prop ks=0.5e6 fric 1000
; cycle 250 =====
end_command
end
; -----
def ff_outlet
ff_outlet = 0
_brad = fc_arg(0)
_bx = fc_arg(1)
_by = fc_arg(2)
_bz = fc_arg(3)
_rad = sqrt(_bx^2 + _by^2)
if (_rad + _brad) > abs(((12 - (_bz + _brad)) / tan(.2222*pi))) then
ff_outlet = 1
end_if
end
; -----
macro zero 'ini xvel 0 yvel 0 zvel 0 xspin 0 yspin 0 zspin 0'
; SET height=12 rad=14.301 rlo=0.1 rhi=.2 poros=0.40; =====
SET height=12 rad=14.301 rlo=0.1 rhi=.35 poros=0.40

make_walls
particle_create
plot create assembly
plot set cap size 25
plot set mag 1.5
plot set rot 0 0 40
plot add ball lorange

pl add wa wire on

pl sh

pause
save example_1-1-brian.SAV
; -----
; restore example_1-1-brian.sav
; -----
; HISTORY
; -----
;
history b xp 0 0 12.00 ;id=1
history b yp 0 0 12.00 ;id=2
history b zp 0 0 12.00 ;id=3
history b xv 0 0 12.00 ;id=4

```

```

history b yv 0 0 12.00 ;id=5
history b zv 0 0 12.00 ;id=6
;
history b xp 0.250 0 11.80 ;id=7
history b yp 0.250 0 11.80 ;id=8
history b zp 0.250 0 11.80 ;id=9
history b xv 0.250 0 11.80 ;id=10
history b yv 0.250 0 11.80 ;id=11
history b zv 0.250 0 11.80 ;id=12
;
history b xp -0.250 0 11.80 ;id=13
history b yp -0.250 0 11.80 ;id=14
history b zp -0.250 0 11.80 ;id=15
history b xv -0.250 0 11.80 ;id=16
history b yv -0.250 0 11.80 ;id=17
history b zv -0.250 0 11.80 ;id=18
;
history b xp 0 0.250 11.80 ;id=19
history b yp 0 0.250 11.80 ;id=20
history b zp 0 0.250 11.80 ;id=21
history b xv 0 0.250 11.80 ;id=22
history b yv 0 0.250 11.80 ;id=23
history b zv 0 0.250 11.80 ;id=24
;
history b xp 0 -0.250 11.80 ;id=25
history b yp 0 -0.250 11.80 ;id=26
history b zp 0 -0.250 11.80 ;id=27
history b xv 0 -0.250 11.80 ;id=28
history b yv 0 -0.250 11.80 ;id=29
history b zv 0 -0.250 11.80 ;id=30
;
history b xp 0.516 0 11.60 ;id=31
history b yp 0.516 0 11.60 ;id=32
history b zp 0.516 0 11.60 ;id=33
history b xv 0.516 0 11.60 ;id=34
history b yv 0.516 0 11.60 ;id=35
history b zv 0.516 0 11.60 ;id=36
;
history b xp -0.516 0 11.60 ;id=37
history b yp -0.516 0 11.60 ;id=38
history b zp -0.516 0 11.60 ;id=39
history b xv -0.516 0 11.60 ;id=40
history b yv -0.516 0 11.60 ;id=41
history b zv -0.516 0 11.60 ;id=42
;
history b xp 0 0.516 11.60 ;id=43
history b yp 0 0.516 11.60 ;id=44
history b zp 0 0.516 11.60 ;id=45

```

```

history b xv 0 0.516 11.60 ;id=46
history b yv 0 0.516 11.60 ;id=47
history b zv 0 0.516 11.60 ;id=48
;
history b xp 0 -0.516 11.60 ;id=49
history b yp 0 -0.516 11.60 ;id=50
history b zp 0 -0.516 11.60 ;id=51
history b xv 0 -0.516 11.60 ;id=52
history b yv 0 -0.516 11.60 ;id=53
history b zv 0 -0.516 11.60 ;id=54
;
history b xp 0.774 0 11.40 ;id=55
history b yp 0.774 0 11.40 ;id=56
history b zp 0.774 0 11.40 ;id=57
history b xv 0.774 0 11.40 ;id=58
history b yv 0.774 0 11.40 ;id=59
history b zv 0.774 0 11.40 ;id=60
;
history b xp -0.774 0 11.40 ;id=61
history b yp -0.774 0 11.40 ;id=62
history b zp -0.774 0 11.40 ;id=63
history b xv -0.774 0 11.40 ;id=64
history b yv -0.774 0 11.40 ;id=65
history b zv -0.774 0 11.40 ;id=66
;
history b xp 0 0.774 11.40 ;id=67
history b yp 0 0.774 11.40 ;id=68
history b zp 0 0.774 11.40 ;id=69
history b xv 0 0.774 11.40 ;id=70
history b yv 0 0.774 11.40 ;id=71
history b zv 0 0.774 11.40 ;id=72
;
history b xp 0 -0.774 11.40 ;id=73
history b yp 0 -0.774 11.40 ;id=74
history b zp 0 -0.774 11.40 ;id=75
history b xv 0 -0.774 11.40 ;id=76
history b yv 0 -0.774 11.40 ;id=77
history b zv 0 -0.774 11.40 ;id=78
;
history b xp 1.03 0 11.20 ;id=79
history b yp 1.03 0 11.20 ;id=80
history b zp 1.03 0 11.20 ;id=81
history b xv 1.03 0 11.20 ;id=82
history b yv 1.03 0 11.20 ;id=83
history b zv 1.03 0 11.20 ;id=84
;
history b xp -1.03 0 11.20 ;id=85
history b yp -1.03 0 11.20 ;id=86

```

```

history b zp -1.03 0 11.20 ;id=87
history b xv -1.03 0 11.20 ;id=88
history b yv -1.03 0 11.20 ;id=89
history b zv -1.03 0 11.20 ;id=90
;
history b xp 0 1.03 11.20 ;id=91
history b yp 0 1.03 11.20 ;id=92
history b zp 0 1.03 11.20 ;id=93
history b xv 0 1.03 11.20 ;id=94
history b yv 0 1.03 11.20 ;id=95
history b zv 0 1.03 11.20 ;id=96
;
history b xp 0 -1.03 11.20 ;id=97
history b yp 0 -1.03 11.20 ;id=98
history b zp 0 -1.03 11.20 ;id=99
history b xv 0 -1.03 11.20 ;id=100
history b yv 0 -1.03 11.20 ;id=101
history b zv 0 -1.03 11.20 ;id=102
;
history b xp 1.29 0 11.00 ;id=103
history b yp 1.29 0 11.00 ;id=104
history b zp 1.29 0 11.00 ;id=105
history b xv 1.29 0 11.00 ;id=106
history b yv 1.29 0 11.00 ;id=107
history b zv 1.29 0 11.00 ;id=108
;
history b xp -1.29 0 11.00 ;id=109
history b yp -1.29 0 11.00 ;id=110
history b zp -1.29 0 11.00 ;id=111
history b xv -1.29 0 11.00 ;id=112
history b yv -1.29 0 11.00 ;id=113
history b zv -1.29 0 11.00 ;id=114
;
history b xp 0 1.29 11.00 ;id=115
history b yp 0 1.29 11.00 ;id=116
history b zp 0 1.29 11.00 ;id=117
history b xv 0 1.29 11.00 ;id=118
history b yv 0 1.29 11.00 ;id=119
history b zv 0 1.29 11.00 ;id=120
;
history b xp 0 -1.29 11.00 ;id=121
history b yp 0 -1.29 11.00 ;id=122
history b zp 0 -1.29 11.00 ;id=123
history b xv 0 -1.29 11.00 ;id=124
history b yv 0 -1.29 11.00 ;id=125
history b zv 0 -1.29 11.00 ;id=126
;
history b xp 2.58 0 10.00 ;id=127

```

```

history b yp 2.58 0 10.00 ;id=128
history b zp 2.58 0 10.00 ;id=129
history b xv 2.58 0 10.00 ;id=130
history b yv 2.58 0 10.00 ;id=131
history b zv 2.58 0 10.00 ;id=132
;
history b xp -2.58 0 10.00 ;id=133
history b yp -2.58 0 10.00 ;id=134
history b zp -2.58 0 10.00 ;id=135
history b xv -2.58 0 10.00 ;id=136
history b yv -2.58 0 10.00 ;id=137
history b zv -2.58 0 10.00 ;id=138
;
history b xp 0 2.58 10.00 ;id=139
history b yp 0 2.58 10.00 ;id=140
history b zp 0 2.58 10.00 ;id=141
history b xv 0 2.58 10.00 ;id=142
history b yv 0 2.58 10.00 ;id=143
history b zv 0 2.58 10.00 ;id=144
;
history b xp 0 -2.58 10.00 ;id=145
history b yp 0 -2.58 10.00 ;id=146
history b zp 0 -2.58 10.00 ;id=147
history b xv 0 -2.58 10.00 ;id=148
history b yv 0 -2.58 10.00 ;id=149
history b zv 0 -2.58 10.00 ;id=150
;
history b xp 3.87 0 9.00 ;id=151
history b yp 3.87 0 9.00 ;id=152
history b zp 3.87 0 9.00 ;id=153
history b xv 3.87 0 9.00 ;id=154
history b yv 3.87 0 9.00 ;id=155
history b zv 3.87 0 9.00 ;id=156
;
history b xp -3.87 0 9.00 ;id=157
history b yp -3.87 0 9.00 ;id=158
history b zp -3.87 0 9.00 ;id=159
history b xv -3.87 0 9.00 ;id=160
history b yv -3.87 0 9.00 ;id=161
history b zv -3.87 0 9.00 ;id=162
;
history b xp 0 3.87 9.00 ;id=163
history b yp 0 3.87 9.00 ;id=164
history b zp 0 3.87 9.00 ;id=165
history b xv 0 3.87 9.00 ;id=166
history b yv 0 3.87 9.00 ;id=167
history b zv 0 3.87 9.00 ;id=168
;

```

```

history b xp 0 -3.87 9.00 ;id=169
history b yp 0 -3.87 9.00 ;id=170
history b zp 0 -3.87 9.00 ;id=171
history b xv 0 -3.87 9.00 ;id=172
history b yv 0 -3.87 9.00 ;id=173
history b zv 0 -3.87 9.00 ;id=174
;
history b xp 5.16 0 8.00 ;id=175
history b yp 5.16 0 8.00 ;id=176
history b zp 5.16 0 8.00 ;id=177
history b xv 5.16 0 8.00 ;id=178
history b yv 5.16 0 8.00 ;id=179
history b zv 5.16 0 8.00 ;id=180
;
history b xp -5.16 0 8.00 ;id=181
history b yp -5.16 0 8.00 ;id=182
history b zp -5.16 0 8.00 ;id=183
history b xv -5.16 0 8.00 ;id=184
history b yv -5.16 0 8.00 ;id=185
history b zv -5.16 0 8.00 ;id=186
;
history b xp 0 5.16 8.00 ;id=187
history b yp 0 5.16 8.00 ;id=188
history b zp 0 5.16 8.00 ;id=189
history b xv 0 5.16 8.00 ;id=190
history b yv 0 5.16 8.00 ;id=191
history b zv 0 5.16 8.00 ;id=192
;
history b xp 0 -5.16 8.00 ;id=193
history b yp 0 -5.16 8.00 ;id=194
history b zp 0 -5.16 8.00 ;id=195
history b xv 0 -5.16 8.00 ;id=196
history b yv 0 -5.16 8.00 ;id=197
history b zv 0 -5.16 8.00 ;id=198
;
history b xp 6.45 0 7.00 ;id=199
history b yp 6.45 0 7.00 ;id=200
history b zp 6.45 0 7.00 ;id=201
history b xv 6.45 0 7.00 ;id=202
history b yv 6.45 0 7.00 ;id=203
history b zv 6.45 0 7.00 ;id=204
;
history b xp -6.45 0 7.00 ;id=205
history b yp -6.45 0 7.00 ;id=206
history b zp -6.45 0 7.00 ;id=207
history b xv -6.45 0 7.00 ;id=208
history b yv -6.45 0 7.00 ;id=209
history b zv -6.45 0 7.00 ;id=210

```

```

;
history b xp 0 6.45 7.00 ;id=211
history b yp 0 6.45 7.00 ;id=212
history b zp 0 6.45 7.00 ;id=213
history b xv 0 6.45 7.00 ;id=214
history b yv 0 6.45 7.00 ;id=215
history b zv 0 6.45 7.00 ;id=216
;
history b xp 0 -6.45 7.00 ;id=217
history b yp 0 -6.45 7.00 ;id=218
history b zp 0 -6.45 7.00 ;id=219
history b xv 0 -6.45 7.00 ;id=220
history b yv 0 -6.45 7.00 ;id=221
history b zv 0 -6.45 7.00 ;id=222
;
history b xp 7.74 0 6.00 ;id=223
history b yp 7.74 0 6.00 ;id=224
history b zp 7.74 0 6.00 ;id=225
history b xv 7.74 0 6.00 ;id=226
history b yv 7.74 0 6.00 ;id=227
history b zv 7.74 0 6.00 ;id=228
;
history b xp -7.74 0 6.00 ;id=229
history b yp -7.74 0 6.00 ;id=230
history b zp -7.74 0 6.00 ;id=231
history b xv -7.74 0 6.00 ;id=232
history b yv -7.74 0 6.00 ;id=233
history b zv -7.74 0 6.00 ;id=234
;
history b xp 0 7.74 6.00 ;id=235
history b yp 0 7.74 6.00 ;id=236
history b zp 0 7.74 6.00 ;id=237
history b xv 0 7.74 6.00 ;id=238
history b yv 0 7.74 6.00 ;id=239
history b zv 0 7.74 6.00 ;id=240
;
history b xp 0 -7.74 6.00 ;id=241
history b yp 0 -7.74 6.00 ;id=242
history b zp 0 -7.74 6.00 ;id=243
history b xv 0 -7.74 6.00 ;id=244
history b yv 0 -7.74 6.00 ;id=245
history b zv 0 -7.74 6.00 ;id=246
;
history b xp 9.03 0 5.00 ;id=247
history b yp 9.03 0 5.00 ;id=248
history b zp 9.03 0 5.00 ;id=249
history b xv 9.03 0 5.00 ;id=250
history b yv 9.03 0 5.00 ;id=251

```

```

history b zv 9.03 0 5.00 ;id=252
;
history b xp -9.03 0 5.00 ;id=253
history b yp -9.03 0 5.00 ;id=254
history b zp -9.03 0 5.00 ;id=255
history b xv -9.03 0 5.00 ;id=256
history b yv -9.03 0 5.00 ;id=257
history b zv -9.03 0 5.00 ;id=258
;
history b xp 0 9.03 5.00 ;id=259
history b yp 0 9.03 5.00 ;id=260
history b zp 0 9.03 5.00 ;id=261
history b xv 0 9.03 5.00 ;id=262
history b yv 0 9.03 5.00 ;id=263
history b zv 0 9.03 5.00 ;id=264
;
history b xp 0 -9.03 5.00 ;id=265
history b yp 0 -9.03 5.00 ;id=266
history b zp 0 -9.03 5.00 ;id=267
history b xv 0 -9.03 5.00 ;id=268
history b yv 0 -9.03 5.00 ;id=269
history b zv 0 -9.03 5.00 ;id=270
;
; -----
; delete wall 5 ; ++++++++ switch order of grav wall delete =====
; set gravity 0 0 -9.81
; cycle 5000

his dia muf ; =====

set grav 0 0 -9.81; =====

cy 3000

save grav1.sav; =====
del wa 5; =====
cy 5000; =====

; -----
save brian12-2-1.sav

cycle 50000
save brian12-2-2.sav

cycle 50000
save brian12-2-3.sav

```

cycle 50000
save brian12-2-4.sav

cycle 50000
save brian12-2-5.sav

cycle 50000
save brian12-2-6.sav

cycle 50000
save brian12-2-7.sav

cycle 50000
save brian12-2-8.sav

cycle 50000
save brian12-2-9.sav

cycle 50000
save brian12-2-10.sav

cycle 50000
save brian12-2-11.sav

cycle 50000
save brian12-2-12.sav

cycle 50000
save brian12-2-13.sav

; -----

; -----

pl sh

12 Meter Pile – 2.5 Discharge Opening

```
;fname: briansPFC12-2.5_ew1.DAT
```

```
; Height=12
```

```
new
```

```
;-----
```

```
def make_walls ; create walls: 5 plate floor
```

```
  wall_kn= 1e10
```

```
command
```

```
  wall id=6 type cylinder end1 0 0 -1 end2 0 0 12 rad 15.4928 kn=wall_kn
```

```
end_command
```

```
command
```

```
  wall id=7 type cylinder end1 0 0 -2 end2 0 0 -14 rad 14.0 14.0 kn=wall_kn
```

```
end_command
```

```
  _x0 = 15
```

```
  _y0 = 15
```

```
  _z0 = -14
```

```
  _x1 = -15
```

```
  _y1 = 15
```

```
  _z1 = -14
```

```
  _x2 = -15
```

```
  _y2 = -15
```

```
  _z2 = -14
```

```
  _x3 = 15
```

```
  _y3 = -15
```

```
  _z3 = -14
```

```
command
```

```
  wall id=8 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) (_x3,_y3,_z3)
```

```
end_command
```

```
  _x0 = 15
```

```
  _y0 = 15
```

```
  _z0 = 0
```

```
  _x1 = -15
```

```
  _y1 = 15
```

```
  _z1 = 0
```

```
  _x2 = -15
```

```
  _y2 = 1.25
```

```
  _z2 = 0
```

```
  _x3 = 15
```

```
  _y3 = 1.25
```

```
  _z3 = 0
```

```
command
```

```
  wall id=1 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
```

```
  (_x3,_y3,_z3)
```

end_command

_x0 = -1.25
_y0 = 2
_z0 = 0
_x1 = -15
_y1 = 2
_z1 = 0
_x2 = -15
_y2 = -2
_z2 = 0
_x3 = -1.25
_y3 = -2
_z3 = 0

command

wall id=2 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
(_x3,_y3,_z3)
end_command

_x0 = 15
_y0 = -1.25
_z0 = 0
_x1 = -15
_y1 = -1.25
_z1 = 0
_x2 = -15
_y2 = -15
_z2 = 0
_x3 = 15
_y3 = -15
_z3 = 0

command

wall id=3 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
(_x3,_y3,_z3)
end_command

_x0 = 15
_y0 = 2
_z0 = 0
_x1 = 1.25
_y1 = 2
_z1 = 0
_x2 = 1.25
_y2 = -2
_z2 = 0
_x3 = 15
_y3 = -2
_z3 = 0

```

command
  wall id=4 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

```

_x0 = 2
_y0 = 2
_z0 = 0
_x1 = -2
_y1 = 2
_z1 = 0
_x2 = -2
_y2 = -2
_z2 = 0
_x3 = 2
_y3 = -2
_z3 = 0

```

```

command
  wall id=5 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

end

```

def particle_create
  s_stiff=0.0 ; initial stiffnesses
  n_stiff=1e6
  tot_vol = (1.0/3.0)* pi * (rad^2.0) * height
  rbar   = 0.5 * (rlo + rhi)
  num    = int((1.0 - poros) * tot_vol / (4.0 / 3.0 * pi * rbar^3))
  mult   = 1.6 ; initial radius multiplication factor
  rlo_0  = rlo / mult
  rhi_0  = rhi / mult
  command
    gen id=1,num rad=rlo_0,rhi_0 x=-14.301,14.301 y=-14.301,14.301 z=0.0,height &
      filter ff_outlet tries 3000000
    prop dens=500 ks=s_stiff kn=n_stiff
  end_command
  ii = out(string(num)+' particles were created')
  sum = 0.0 ; get actual porosity
  bp = ball_head
  loop while bp # null
    sum = sum + 4.0 / 3.0 * pi * b_rad(bp)^3
    bp = b_next(bp)
  end_loop
  pmeas = 1.0 - sum / tot_vol
  mult = ((1.0 - poros) / (1.0 - pmeas))^(1.0/3.0)
  command

```

```

ini rad mul mult
; cycle 1000 =====
; prop ks=0.5e6 fric 0.4 =====
prop ks=0.5e6 fric 1000
; cycle 250 =====
end_command
end
; -----
def ff_outlet
ff_outlet = 0
_brad = fc_arg(0)
_bx = fc_arg(1)
_by = fc_arg(2)
_bz = fc_arg(3)
_rad = sqrt(_bx^2 + _by^2)
if (_rad + _brad) > abs(((12 - (_bz + _brad)) / tan(.2222*pi))) then
ff_outlet = 1
end_if
end
; -----
macro zero 'ini xvel 0 yvel 0 zvel 0 xspin 0 yspin 0 zspin 0'
; SET height=12 rad=14.301 rlo=0.1 rhi=.2 poros=0.40; =====
SET height=12 rad=14.301 rlo=0.1 rhi=.35 poros=0.40

make_walls
particle_create
plot create assembly
plot set cap size 25
plot set mag 1.5
plot set rot 0 0 40
plot add ball lorange

pl add wa wire on

pl sh

pause
save example_1-1-brian.SAV
; -----
; restore example_1-1-brian.sav
; -----
; HISTORY
; -----
;
history b xp 0 0 12.00 ;id=1
history b yp 0 0 12.00 ;id=2
history b zp 0 0 12.00 ;id=3
history b xv 0 0 12.00 ;id=4

```

```

history b yv 0 0 12.00 ;id=5
history b zv 0 0 12.00 ;id=6
;
history b xp 0.250 0 11.80 ;id=7
history b yp 0.250 0 11.80 ;id=8
history b zp 0.250 0 11.80 ;id=9
history b xv 0.250 0 11.80 ;id=10
history b yv 0.250 0 11.80 ;id=11
history b zv 0.250 0 11.80 ;id=12
;
history b xp -0.250 0 11.80 ;id=13
history b yp -0.250 0 11.80 ;id=14
history b zp -0.250 0 11.80 ;id=15
history b xv -0.250 0 11.80 ;id=16
history b yv -0.250 0 11.80 ;id=17
history b zv -0.250 0 11.80 ;id=18
;
history b xp 0 0.250 11.80 ;id=19
history b yp 0 0.250 11.80 ;id=20
history b zp 0 0.250 11.80 ;id=21
history b xv 0 0.250 11.80 ;id=22
history b yv 0 0.250 11.80 ;id=23
history b zv 0 0.250 11.80 ;id=24
;
history b xp 0 -0.250 11.80 ;id=25
history b yp 0 -0.250 11.80 ;id=26
history b zp 0 -0.250 11.80 ;id=27
history b xv 0 -0.250 11.80 ;id=28
history b yv 0 -0.250 11.80 ;id=29
history b zv 0 -0.250 11.80 ;id=30
;
history b xp 0.516 0 11.60 ;id=31
history b yp 0.516 0 11.60 ;id=32
history b zp 0.516 0 11.60 ;id=33
history b xv 0.516 0 11.60 ;id=34
history b yv 0.516 0 11.60 ;id=35
history b zv 0.516 0 11.60 ;id=36
;
history b xp -0.516 0 11.60 ;id=37
history b yp -0.516 0 11.60 ;id=38
history b zp -0.516 0 11.60 ;id=39
history b xv -0.516 0 11.60 ;id=40
history b yv -0.516 0 11.60 ;id=41
history b zv -0.516 0 11.60 ;id=42
;
history b xp 0 0.516 11.60 ;id=43
history b yp 0 0.516 11.60 ;id=44
history b zp 0 0.516 11.60 ;id=45

```

```

history b xv 0 0.516 11.60 ;id=46
history b yv 0 0.516 11.60 ;id=47
history b zv 0 0.516 11.60 ;id=48
;
history b xp 0 -0.516 11.60 ;id=49
history b yp 0 -0.516 11.60 ;id=50
history b zp 0 -0.516 11.60 ;id=51
history b xv 0 -0.516 11.60 ;id=52
history b yv 0 -0.516 11.60 ;id=53
history b zv 0 -0.516 11.60 ;id=54
;
history b xp 0.774 0 11.40 ;id=55
history b yp 0.774 0 11.40 ;id=56
history b zp 0.774 0 11.40 ;id=57
history b xv 0.774 0 11.40 ;id=58
history b yv 0.774 0 11.40 ;id=59
history b zv 0.774 0 11.40 ;id=60
;
history b xp -0.774 0 11.40 ;id=61
history b yp -0.774 0 11.40 ;id=62
history b zp -0.774 0 11.40 ;id=63
history b xv -0.774 0 11.40 ;id=64
history b yv -0.774 0 11.40 ;id=65
history b zv -0.774 0 11.40 ;id=66
;
history b xp 0 0.774 11.40 ;id=67
history b yp 0 0.774 11.40 ;id=68
history b zp 0 0.774 11.40 ;id=69
history b xv 0 0.774 11.40 ;id=70
history b yv 0 0.774 11.40 ;id=71
history b zv 0 0.774 11.40 ;id=72
;
history b xp 0 -0.774 11.40 ;id=73
history b yp 0 -0.774 11.40 ;id=74
history b zp 0 -0.774 11.40 ;id=75
history b xv 0 -0.774 11.40 ;id=76
history b yv 0 -0.774 11.40 ;id=77
history b zv 0 -0.774 11.40 ;id=78
;
history b xp 1.03 0 11.20 ;id=79
history b yp 1.03 0 11.20 ;id=80
history b zp 1.03 0 11.20 ;id=81
history b xv 1.03 0 11.20 ;id=82
history b yv 1.03 0 11.20 ;id=83
history b zv 1.03 0 11.20 ;id=84
;
history b xp -1.03 0 11.20 ;id=85
history b yp -1.03 0 11.20 ;id=86

```

```

history b zp -1.03 0 11.20 ;id=87
history b xv -1.03 0 11.20 ;id=88
history b yv -1.03 0 11.20 ;id=89
history b zv -1.03 0 11.20 ;id=90
;
history b xp 0 1.03 11.20 ;id=91
history b yp 0 1.03 11.20 ;id=92
history b zp 0 1.03 11.20 ;id=93
history b xv 0 1.03 11.20 ;id=94
history b yv 0 1.03 11.20 ;id=95
history b zv 0 1.03 11.20 ;id=96
;
history b xp 0 -1.03 11.20 ;id=97
history b yp 0 -1.03 11.20 ;id=98
history b zp 0 -1.03 11.20 ;id=99
history b xv 0 -1.03 11.20 ;id=100
history b yv 0 -1.03 11.20 ;id=101
history b zv 0 -1.03 11.20 ;id=102
;
history b xp 1.29 0 11.00 ;id=103
history b yp 1.29 0 11.00 ;id=104
history b zp 1.29 0 11.00 ;id=105
history b xv 1.29 0 11.00 ;id=106
history b yv 1.29 0 11.00 ;id=107
history b zv 1.29 0 11.00 ;id=108
;
history b xp -1.29 0 11.00 ;id=109
history b yp -1.29 0 11.00 ;id=110
history b zp -1.29 0 11.00 ;id=111
history b xv -1.29 0 11.00 ;id=112
history b yv -1.29 0 11.00 ;id=113
history b zv -1.29 0 11.00 ;id=114
;
history b xp 0 1.29 11.00 ;id=115
history b yp 0 1.29 11.00 ;id=116
history b zp 0 1.29 11.00 ;id=117
history b xv 0 1.29 11.00 ;id=118
history b yv 0 1.29 11.00 ;id=119
history b zv 0 1.29 11.00 ;id=120
;
history b xp 0 -1.29 11.00 ;id=121
history b yp 0 -1.29 11.00 ;id=122
history b zp 0 -1.29 11.00 ;id=123
history b xv 0 -1.29 11.00 ;id=124
history b yv 0 -1.29 11.00 ;id=125
history b zv 0 -1.29 11.00 ;id=126
;
history b xp 2.58 0 10.00 ;id=127

```

```

history b yp 2.58 0 10.00 ;id=128
history b zp 2.58 0 10.00 ;id=129
history b xv 2.58 0 10.00 ;id=130
history b yv 2.58 0 10.00 ;id=131
history b zv 2.58 0 10.00 ;id=132
;
history b xp -2.58 0 10.00 ;id=133
history b yp -2.58 0 10.00 ;id=134
history b zp -2.58 0 10.00 ;id=135
history b xv -2.58 0 10.00 ;id=136
history b yv -2.58 0 10.00 ;id=137
history b zv -2.58 0 10.00 ;id=138
;
history b xp 0 2.58 10.00 ;id=139
history b yp 0 2.58 10.00 ;id=140
history b zp 0 2.58 10.00 ;id=141
history b xv 0 2.58 10.00 ;id=142
history b yv 0 2.58 10.00 ;id=143
history b zv 0 2.58 10.00 ;id=144
;
history b xp 0 -2.58 10.00 ;id=145
history b yp 0 -2.58 10.00 ;id=146
history b zp 0 -2.58 10.00 ;id=147
history b xv 0 -2.58 10.00 ;id=148
history b yv 0 -2.58 10.00 ;id=149
history b zv 0 -2.58 10.00 ;id=150
;
history b xp 3.87 0 9.00 ;id=151
history b yp 3.87 0 9.00 ;id=152
history b zp 3.87 0 9.00 ;id=153
history b xv 3.87 0 9.00 ;id=154
history b yv 3.87 0 9.00 ;id=155
history b zv 3.87 0 9.00 ;id=156
;
history b xp -3.87 0 9.00 ;id=157
history b yp -3.87 0 9.00 ;id=158
history b zp -3.87 0 9.00 ;id=159
history b xv -3.87 0 9.00 ;id=160
history b yv -3.87 0 9.00 ;id=161
history b zv -3.87 0 9.00 ;id=162
;
history b xp 0 3.87 9.00 ;id=163
history b yp 0 3.87 9.00 ;id=164
history b zp 0 3.87 9.00 ;id=165
history b xv 0 3.87 9.00 ;id=166
history b yv 0 3.87 9.00 ;id=167
history b zv 0 3.87 9.00 ;id=168
;

```

```

history b xp 0 -3.87 9.00 ;id=169
history b yp 0 -3.87 9.00 ;id=170
history b zp 0 -3.87 9.00 ;id=171
history b xv 0 -3.87 9.00 ;id=172
history b yv 0 -3.87 9.00 ;id=173
history b zv 0 -3.87 9.00 ;id=174
;
history b xp 5.16 0 8.00 ;id=175
history b yp 5.16 0 8.00 ;id=176
history b zp 5.16 0 8.00 ;id=177
history b xv 5.16 0 8.00 ;id=178
history b yv 5.16 0 8.00 ;id=179
history b zv 5.16 0 8.00 ;id=180
;
history b xp -5.16 0 8.00 ;id=181
history b yp -5.16 0 8.00 ;id=182
history b zp -5.16 0 8.00 ;id=183
history b xv -5.16 0 8.00 ;id=184
history b yv -5.16 0 8.00 ;id=185
history b zv -5.16 0 8.00 ;id=186
;
history b xp 0 5.16 8.00 ;id=187
history b yp 0 5.16 8.00 ;id=188
history b zp 0 5.16 8.00 ;id=189
history b xv 0 5.16 8.00 ;id=190
history b yv 0 5.16 8.00 ;id=191
history b zv 0 5.16 8.00 ;id=192
;
history b xp 0 -5.16 8.00 ;id=193
history b yp 0 -5.16 8.00 ;id=194
history b zp 0 -5.16 8.00 ;id=195
history b xv 0 -5.16 8.00 ;id=196
history b yv 0 -5.16 8.00 ;id=197
history b zv 0 -5.16 8.00 ;id=198
;
history b xp 6.45 0 7.00 ;id=199
history b yp 6.45 0 7.00 ;id=200
history b zp 6.45 0 7.00 ;id=201
history b xv 6.45 0 7.00 ;id=202
history b yv 6.45 0 7.00 ;id=203
history b zv 6.45 0 7.00 ;id=204
;
history b xp -6.45 0 7.00 ;id=205
history b yp -6.45 0 7.00 ;id=206
history b zp -6.45 0 7.00 ;id=207
history b xv -6.45 0 7.00 ;id=208
history b yv -6.45 0 7.00 ;id=209
history b zv -6.45 0 7.00 ;id=210

```

```

;
history b xp 0 6.45 7.00 ;id=211
history b yp 0 6.45 7.00 ;id=212
history b zp 0 6.45 7.00 ;id=213
history b xv 0 6.45 7.00 ;id=214
history b yv 0 6.45 7.00 ;id=215
history b zv 0 6.45 7.00 ;id=216
;
history b xp 0 -6.45 7.00 ;id=217
history b yp 0 -6.45 7.00 ;id=218
history b zp 0 -6.45 7.00 ;id=219
history b xv 0 -6.45 7.00 ;id=220
history b yv 0 -6.45 7.00 ;id=221
history b zv 0 -6.45 7.00 ;id=222
;
history b xp 7.74 0 6.00 ;id=223
history b yp 7.74 0 6.00 ;id=224
history b zp 7.74 0 6.00 ;id=225
history b xv 7.74 0 6.00 ;id=226
history b yv 7.74 0 6.00 ;id=227
history b zv 7.74 0 6.00 ;id=228
;
history b xp -7.74 0 6.00 ;id=229
history b yp -7.74 0 6.00 ;id=230
history b zp -7.74 0 6.00 ;id=231
history b xv -7.74 0 6.00 ;id=232
history b yv -7.74 0 6.00 ;id=233
history b zv -7.74 0 6.00 ;id=234
;
history b xp 0 7.74 6.00 ;id=235
history b yp 0 7.74 6.00 ;id=236
history b zp 0 7.74 6.00 ;id=237
history b xv 0 7.74 6.00 ;id=238
history b yv 0 7.74 6.00 ;id=239
history b zv 0 7.74 6.00 ;id=240
;
history b xp 0 -7.74 6.00 ;id=241
history b yp 0 -7.74 6.00 ;id=242
history b zp 0 -7.74 6.00 ;id=243
history b xv 0 -7.74 6.00 ;id=244
history b yv 0 -7.74 6.00 ;id=245
history b zv 0 -7.74 6.00 ;id=246
;
history b xp 9.03 0 5.00 ;id=247
history b yp 9.03 0 5.00 ;id=248
history b zp 9.03 0 5.00 ;id=249
history b xv 9.03 0 5.00 ;id=250
history b yv 9.03 0 5.00 ;id=251

```

```

history b zv 9.03 0 5.00 ;id=252
;
history b xp -9.03 0 5.00 ;id=253
history b yp -9.03 0 5.00 ;id=254
history b zp -9.03 0 5.00 ;id=255
history b xv -9.03 0 5.00 ;id=256
history b yv -9.03 0 5.00 ;id=257
history b zv -9.03 0 5.00 ;id=258
;
history b xp 0 9.03 5.00 ;id=259
history b yp 0 9.03 5.00 ;id=260
history b zp 0 9.03 5.00 ;id=261
history b xv 0 9.03 5.00 ;id=262
history b yv 0 9.03 5.00 ;id=263
history b zv 0 9.03 5.00 ;id=264
;
history b xp 0 -9.03 5.00 ;id=265
history b yp 0 -9.03 5.00 ;id=266
history b zp 0 -9.03 5.00 ;id=267
history b xv 0 -9.03 5.00 ;id=268
history b yv 0 -9.03 5.00 ;id=269
history b zv 0 -9.03 5.00 ;id=270
;
; -----
; delete wall 5 ; ++++++++ switch order of grav wall delete =====
; set gravity 0 0 -9.81
; cycle 5000

his dia muf ; =====

set grav 0 0 -9.81; =====

cy 3000

save grav1.sav; =====
del wa 5; =====
cy 5000; =====

; -----
save brian12-2.5-1.sav

cycle 50000
save brian12-2.5-2.sav

cycle 50000
save brian12-2.5-3.sav

```

cycle 50000
save brian12-2.5-4.sav

cycle 50000
save brian12-2.5-5.sav

cycle 50000
save brian12-2.5-6.sav

cycle 50000
save brian12-2.5-7.sav

cycle 50000
save brian12-2.5-8.sav

cycle 50000
save brian12-2.5-9.sav

cycle 50000
save brian12-2.5-10.sav

cycle 50000
save brian12-2.5-11.sav

cycle 50000
save brian12-2.5-12.sav

cycle 50000
save brian12-2.5-13.sav

; -----

; -----

pl sh

14 Meter Pile – 2.0 Discharge Opening

```
;fname: briansPFC14-2DAT
```

```
; Height=14
```

```
new
```

```
;-----
```

```
def make_walls ; create walls: 5 plate floor
```

```
  wall_kn= 1e10
```

```
command
```

```
  wall id=6 type cylinder end1 0 0 -1 end2 0 0 14 rad 17.605 kn=wall_kn
```

```
end_command
```

```
command
```

```
  wall id=7 type cylinder end1 0 0 -2 end2 0 0 -14 rad 14.0 14.0 kn=wall_kn
```

```
end_command
```

```
_x0 = 15
```

```
_y0 = 15
```

```
_z0 = -14
```

```
_x1 = -15
```

```
_y1 = 15
```

```
_z1 = -14
```

```
_x2 = -15
```

```
_y2 = -15
```

```
_z2 = -14
```

```
_x3 = 15
```

```
_y3 = -15
```

```
_z3 = -14
```

```
command
```

```
  wall id=8 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) (_x3,_y3,_z3)
```

```
end_command
```

```
_x0 = 19
```

```
_y0 = 19
```

```
_z0 = 0
```

```
_x1 = -19
```

```
_y1 = 19
```

```
_z1 = 0
```

```
_x2 = -19
```

```
_y2 = 1
```

```
_z2 = 0
```

```
_x3 = 19
```

```
_y3 = 1
```

```
_z3 = 0
```

```
command
```

```
  wall id=1 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
```

```
  (_x3,_y3,_z3)
```

end_command

_x0 = -1
_y0 = 2
_z0 = 0
_x1 = -19
_y1 = 2
_z1 = 0
_x2 = -19
_y2 = -2
_z2 = 0
_x3 = -1
_y3 = -2
_z3 = 0

command

wall id=2 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
(_x3,_y3,_z3)
end_command

_x0 = 19
_y0 = -1
_z0 = 0
_x1 = -19
_y1 = -1
_z1 = 0
_x2 = -19
_y2 = -19
_z2 = 0
_x3 = 19
_y3 = -19
_z3 = 0

command

wall id=3 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
(_x3,_y3,_z3)
end_command

_x0 = 19
_y0 = 2
_z0 = 0
_x1 = 1
_y1 = 2
_z1 = 0
_x2 = 1
_y2 = -2
_z2 = 0
_x3 = 19
_y3 = -2
_z3 = 0

```

command
  wall id=4 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

```

_x0 = 2
_y0 = 2
_z0 = 0
_x1 = -2
_y1 = 2
_z1 = 0
_x2 = -2
_y2 = -2
_z2 = 0
_x3 = 2
_y3 = -2
_z3 = 0

```

```

command
  wall id=5 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

end

```

def particle_create
  s_stiff=0.0 ; initial stiffnesses
  n_stiff=1e6
  tot_vol = (1.0/3.0)* pi * (rad^2.0) * height
  rbar   = 0.5 * (rlo + rhi)
  num    = int((1.0 - poros) * tot_vol / (4.0 / 3.0 * pi * rbar^3))
  mult   = 1.6 ; initial radius multiplication factor
  rlo_0  = rlo / mult
  rhi_0  = rhi / mult
  command
    gen id=1,num rad=rlo_0,rhi_0 x=-16.431,16.431 y=-16.431,16.431 z=0.0,height &
      filter ff_outlet tries 3000000
    prop dens=500 ks=s_stiff kn=n_stiff
  end_command
  ii = out(string(num)+' particles were created')
  sum = 0.0 ; get actual porosity
  bp = ball_head
  loop while bp # null
    sum = sum + 4.0 / 3.0 * pi * b_rad(bp)^3
    bp = b_next(bp)
  end_loop
  pmeas = 1.0 - sum / tot_vol
  mult = ((1.0 - poros) / (1.0 - pmeas))^(1.0/3.0)
  command

```

```

ini rad mul mult
; cycle 1000 =====
; prop ks=0.5e6 fric 0.4 =====
prop ks=0.5e6 fric 1000
end_command
end
; -----
def ff_outlet
ff_outlet = 0
_brad = fc_arg(0)
_bx = fc_arg(1)
_by = fc_arg(2)
_bz = fc_arg(3)
_rad = sqrt(_bx^2 + _by^2)
if (_rad + _brad) > abs(((14 - (_bz + _brad)) / tan(.2222*pi))) then
ff_outlet = 1
end_if
end
; -----
macro zero 'ini xvel 0 yvel 0 zvel 0 xspin 0 yspin 0 zspin 0'
SET height=14 rad=16.431 rlo=0.1 rhi=.35 poros=0.40

make_walls
particle_create
plot create assembly
plot set cap size 25
plot set mag 1.5
plot set rot 0 0 40
plot add ball lorange

pl add wa wire on

pl sh

pause
save example_1-1-brian.SAV
; -----
; restore example_1-1-brian.sav
; -----
; HISTORY
; -----
;
history b xp 0 0 14.00 ;id=1
history b yp 0 0 14.00 ;id=2
history b zp 0 0 14.00 ;id=3
history b xv 0 0 14.00 ;id=4
history b yv 0 0 14.00 ;id=5
history b zv 0 0 14.00 ;id=6

```

```

;
history b xp 0.234 0 13.80 ;id=7
history b yp 0.234 0 13.80 ;id=8
history b zp 0.234 0 13.80 ;id=9
history b xv 0.234 0 13.80 ;id=10
history b yv 0.234 0 13.80 ;id=11
history b zv 0.234 0 13.80 ;id=12
;
history b xp -0.234 0 13.80 ;id=13
history b yp -0.234 0 13.80 ;id=14
history b zp -0.234 0 13.80 ;id=15
history b xv -0.234 0 13.80 ;id=16
history b yv -0.234 0 13.80 ;id=17
history b zv -0.234 0 13.80 ;id=18
;
history b xp 0 0.234 13.80 ;id=19
history b yp 0 0.234 13.80 ;id=20
history b zp 0 0.234 13.80 ;id=21
history b xv 0 0.234 13.80 ;id=22
history b yv 0 0.234 13.80 ;id=23
history b zv 0 0.234 13.80 ;id=24
;
history b xp 0 -0.234 13.80 ;id=25
history b yp 0 -0.234 13.80 ;id=26
history b zp 0 -0.234 13.80 ;id=27
history b xv 0 -0.234 13.80 ;id=28
history b yv 0 -0.234 13.80 ;id=29
history b zv 0 -0.234 13.80 ;id=30
;
history b xp 0.469 0 13.60 ;id=31
history b yp 0.469 0 13.60 ;id=32
history b zp 0.469 0 13.60 ;id=33
history b xv 0.469 0 13.60 ;id=34
history b yv 0.469 0 13.60 ;id=35
history b zv 0.469 0 13.60 ;id=36
;
history b xp -0.469 0 13.60 ;id=37
history b yp -0.469 0 13.60 ;id=38
history b zp -0.469 0 13.60 ;id=39
history b xv -0.469 0 13.60 ;id=40
history b yv -0.469 0 13.60 ;id=41
history b zv -0.469 0 13.60 ;id=42
;
history b xp 0 0.469 13.60 ;id=43
history b yp 0 0.469 13.60 ;id=44
history b zp 0 0.469 13.60 ;id=45
history b xv 0 0.469 13.60 ;id=46
history b yv 0 0.469 13.60 ;id=47

```

```

history b zv 0 0.469 13.60 ;id=48
;
history b xp 0 -0.469 13.60 ;id=49
history b yp 0 -0.469 13.60 ;id=50
history b zp 0 -0.469 13.60 ;id=51
history b xv 0 -0.469 13.60 ;id=52
history b yv 0 -0.469 13.60 ;id=53
history b zv 0 -0.469 13.60 ;id=54
;
history b xp 0.704 0 13.40 ;id=55
history b yp 0.704 0 13.40 ;id=56
history b zp 0.704 0 13.40 ;id=57
history b xv 0.704 0 13.40 ;id=58
history b yv 0.704 0 13.40 ;id=59
history b zv 0.704 0 13.40 ;id=60
;
history b xp -0.704 0 13.40 ;id=61
history b yp -0.704 0 13.40 ;id=62
history b zp -0.704 0 13.40 ;id=63
history b xv -0.704 0 13.40 ;id=64
history b yv -0.704 0 13.40 ;id=65
history b zv -0.704 0 13.40 ;id=66
;
history b xp 0 0.704 13.40 ;id=67
history b yp 0 0.704 13.40 ;id=68
history b zp 0 0.704 13.40 ;id=69
history b xv 0 0.704 13.40 ;id=70
history b yv 0 0.704 13.40 ;id=71
history b zv 0 0.704 13.40 ;id=72
;
history b xp 0 -0.704 13.40 ;id=73
history b yp 0 -0.704 13.40 ;id=74
history b zp 0 -0.704 13.40 ;id=75
history b xv 0 -0.704 13.40 ;id=76
history b yv 0 -0.704 13.40 ;id=77
history b zv 0 -0.704 13.40 ;id=78
;
history b xp 0.938 0 13.20 ;id=79
history b yp 0.938 0 13.20 ;id=80
history b zp 0.938 0 13.20 ;id=81
history b xv 0.938 0 13.20 ;id=82
history b yv 0.938 0 13.20 ;id=83
history b zv 0.938 0 13.20 ;id=84
;
history b xp -0.938 0 13.20 ;id=85
history b yp -0.938 0 13.20 ;id=86
history b zp -0.938 0 13.20 ;id=87
history b xv -0.938 0 13.20 ;id=88

```

```

history b yv -0.938 0 13.20 ;id=89
history b zv -0.938 0 13.20 ;id=90
;
history b xp 0 0.938 13.20 ;id=91
history b yp 0 0.938 13.20 ;id=92
history b zp 0 0.938 13.20 ;id=93
history b xv 0 0.938 13.20 ;id=94
history b yv 0 0.938 13.20 ;id=95
history b zv 0 0.938 13.20 ;id=96
;
history b xp 0 -0.938 13.20 ;id=97
history b yp 0 -0.938 13.20 ;id=98
history b zp 0 -0.938 13.20 ;id=99
history b xv 0 -0.938 13.20 ;id=100
history b yv 0 -0.938 13.20 ;id=101
history b zv 0 -0.938 13.20 ;id=102
;
history b xp 1.17 0 13.00 ;id=103
history b yp 1.17 0 13.00 ;id=104
history b zp 1.17 0 13.00 ;id=105
history b xv 1.17 0 13.00 ;id=106
history b yv 1.17 0 13.00 ;id=107
history b zv 1.17 0 13.00 ;id=108
;
history b xp -1.17 0 13.00 ;id=109
history b yp -1.17 0 13.00 ;id=110
history b zp -1.17 0 13.00 ;id=111
history b xv -1.17 0 13.00 ;id=112
history b yv -1.17 0 13.00 ;id=113
history b zv -1.17 0 13.00 ;id=114
;
history b xp 0 1.17 13.00 ;id=115
history b yp 0 1.17 13.00 ;id=116
history b zp 0 1.17 13.00 ;id=117
history b xv 0 1.17 13.00 ;id=118
history b yv 0 1.17 13.00 ;id=119
history b zv 0 1.17 13.00 ;id=120
;
history b xp 0 -1.17 13.00 ;id=121
history b yp 0 -1.17 13.00 ;id=122
history b zp 0 -1.17 13.00 ;id=123
history b xv 0 -1.17 13.00 ;id=124
history b yv 0 -1.17 13.00 ;id=125
history b zv 0 -1.17 13.00 ;id=126
;
history b xp 2.34 0 12.00 ;id=127
history b yp 2.34 0 12.00 ;id=128
history b zp 2.34 0 12.00 ;id=129

```

```

history b xv 2.34 0 12.00 ;id=130
history b yv 2.34 0 12.00 ;id=131
history b zv 2.34 0 12.00 ;id=132
;
history b xp -2.34 0 12.00 ;id=133
history b yp -2.34 0 12.00 ;id=134
history b zp -2.34 0 12.00 ;id=135
history b xv -2.34 0 12.00 ;id=136
history b yv -2.34 0 12.00 ;id=137
history b zv -2.34 0 12.00 ;id=138
;
history b xp 0 2.34 12.00 ;id=139
history b yp 0 2.34 12.00 ;id=140
history b zp 0 2.34 12.00 ;id=141
history b xv 0 2.34 12.00 ;id=142
history b yv 0 2.34 12.00 ;id=143
history b zv 0 2.34 12.00 ;id=144
;
history b xp 0 -2.34 12.00 ;id=145
history b yp 0 -2.34 12.00 ;id=146
history b zp 0 -2.34 12.00 ;id=147
history b xv 0 -2.34 12.00 ;id=148
history b yv 0 -2.34 12.00 ;id=149
history b zv 0 -2.34 12.00 ;id=150
;
history b xp 3.52 0 11.00 ;id=151
history b yp 3.52 0 11.00 ;id=152
history b zp 3.52 0 11.00 ;id=153
history b xv 3.52 0 11.00 ;id=154
history b yv 3.52 0 11.00 ;id=155
history b zv 3.52 0 11.00 ;id=156
;
history b xp -3.52 0 11.00 ;id=157
history b yp -3.52 0 11.00 ;id=158
history b zp -3.52 0 11.00 ;id=159
history b xv -3.52 0 11.00 ;id=160
history b yv -3.52 0 11.00 ;id=161
history b zv -3.52 0 11.00 ;id=162
;
history b xp 0 3.52 11.00 ;id=163
history b yp 0 3.52 11.00 ;id=164
history b zp 0 3.52 11.00 ;id=165
history b xv 0 3.52 11.00 ;id=166
history b yv 0 3.52 11.00 ;id=167
history b zv 0 3.52 11.00 ;id=168
;
history b xp 0 -3.52 11.00 ;id=169
history b yp 0 -3.52 11.00 ;id=170

```

```

history b zp 0 -3.52 11.00 ;id=171
history b xv 0 -3.52 11.00 ;id=172
history b yv 0 -3.52 11.00 ;id=173
history b zv 0 -3.52 11.00 ;id=174
;
history b xp 4.69 0 10.00 ;id=175
history b yp 4.69 0 10.00 ;id=176
history b zp 4.69 0 10.00 ;id=177
history b xv 4.69 0 10.00 ;id=178
history b yv 4.69 0 10.00 ;id=179
history b zv 4.69 0 10.00 ;id=180
;
history b xp -4.69 0 10.00 ;id=181
history b yp -4.69 0 10.00 ;id=182
history b zp -4.69 0 10.00 ;id=183
history b xv -4.69 0 10.00 ;id=184
history b yv -4.69 0 10.00 ;id=185
history b zv -4.69 0 10.00 ;id=186
;
history b xp 0 4.69 10.00 ;id=187
history b yp 0 4.69 10.00 ;id=188
history b zp 0 4.69 10.00 ;id=189
history b xv 0 4.69 10.00 ;id=190
history b yv 0 4.69 10.00 ;id=191
history b zv 0 4.69 10.00 ;id=192
;
history b xp 0 -4.69 10.00 ;id=193
history b yp 0 -4.69 10.00 ;id=194
history b zp 0 -4.69 10.00 ;id=195
history b xv 0 -4.69 10.00 ;id=196
history b yv 0 -4.69 10.00 ;id=197
history b zv 0 -4.69 10.00 ;id=198
;
history b xp 5.86 0 9.00 ;id=199
history b yp 5.86 0 9.00 ;id=200
history b zp 5.86 0 9.00 ;id=201
history b xv 5.86 0 9.00 ;id=202
history b yv 5.86 0 9.00 ;id=203
history b zv 5.86 0 9.00 ;id=204
;
history b xp -5.86 0 9.00 ;id=205
history b yp -5.86 0 9.00 ;id=206
history b zp -5.86 0 9.00 ;id=207
history b xv -5.86 0 9.00 ;id=208
history b yv -5.86 0 9.00 ;id=209
history b zv -5.86 0 9.00 ;id=210
;
history b xp 0 5.86 9.00 ;id=211

```

```

history b yp 0 5.86 9.00 ;id=212
history b zp 0 5.86 9.00 ;id=213
history b xv 0 5.86 9.00 ;id=214
history b yv 0 5.86 9.00 ;id=215
history b zv 0 5.86 9.00 ;id=216
;
history b xp 0 -5.86 9.00 ;id=217
history b yp 0 -5.86 9.00 ;id=218
history b zp 0 -5.86 9.00 ;id=219
history b xv 0 -5.86 9.00 ;id=220
history b yv 0 -5.86 9.00 ;id=221
history b zv 0 -5.86 9.00 ;id=222
;
history b xp 7.04 0 8.00 ;id=223
history b yp 7.04 0 8.00 ;id=224
history b zp 7.04 0 8.00 ;id=225
history b xv 7.04 0 8.00 ;id=226
history b yv 7.04 0 8.00 ;id=227
history b zv 7.04 0 8.00 ;id=228
;
history b xp -7.04 0 8.00 ;id=229
history b yp -7.04 0 8.00 ;id=230
history b zp -7.04 0 8.00 ;id=231
history b xv -7.04 0 8.00 ;id=232
history b yv -7.04 0 8.00 ;id=233
history b zv -7.04 0 8.00 ;id=234
;
history b xp 0 7.04 8.00 ;id=235
history b yp 0 7.04 8.00 ;id=236
history b zp 0 7.04 8.00 ;id=237
history b xv 0 7.04 8.00 ;id=238
history b yv 0 7.04 8.00 ;id=239
history b zv 0 7.04 8.00 ;id=240
;
history b xp 0 -7.04 8.00 ;id=241
history b yp 0 -7.04 8.00 ;id=242
history b zp 0 -7.04 8.00 ;id=243
history b xv 0 -7.04 8.00 ;id=244
history b yv 0 -7.04 8.00 ;id=245
history b zv 0 -7.04 8.00 ;id=246
;
history b xp 8.21 0 7.00 ;id=247
history b yp 8.21 0 7.00 ;id=248
history b zp 8.21 0 7.00 ;id=249
history b xv 8.21 0 7.00 ;id=250
history b yv 8.21 0 7.00 ;id=251
history b zv 8.21 0 7.00 ;id=252
;

```

```

history b xp -8.21 0 7.00 ;id=253
history b yp -8.21 0 7.00 ;id=254
history b zp -8.21 0 7.00 ;id=255
history b xv -8.21 0 7.00 ;id=256
history b yv -8.21 0 7.00 ;id=257
history b zv -8.21 0 7.00 ;id=258
;
history b xp 0 8.21 7.00 ;id=259
history b yp 0 8.21 7.00 ;id=260
history b zp 0 8.21 7.00 ;id=261
history b xv 0 8.21 7.00 ;id=262
history b yv 0 8.21 7.00 ;id=263
history b zv 0 8.21 7.00 ;id=264
;
history b xp 0 -8.21 7.00 ;id=265
history b yp 0 -8.21 7.00 ;id=266
history b zp 0 -8.21 7.00 ;id=267
history b xv 0 -8.21 7.00 ;id=268
history b yv 0 -8.21 7.00 ;id=269
history b zv 0 -8.21 7.00 ;id=270
;
; -----
; delete wall 5 ; ++++++ switch order of grav wall delete =====
; set gravity 0 0 -9.81
; cycle 5000

his dia muf ; =====

set grav 0 0 -9.81; =====

cy 3000

save grav1.sav; =====
del wa 5; =====
cy 5000; =====

; -----
save brian14-2-1.sav

cycle 50000
save brian14-2-2.sav

cycle 50000
save brian14-2-3.sav

cycle 50000

```

save brian14-2-4.sav

cycle 50000
save brian14-2-5.sav

cycle 50000
save brian14-2-6.sav

cycle 50000
save brian14-2-7.sav

cycle 50000
save brian14-2-8.sav

cycle 50000
save brian14-2-9.sav

cycle 50000
save brian14-2-10.sav

cycle 50000
save brian14-2-11.sav

cycle 50000
save brian14-2-12.sav

cycle 50000
save brian14-2-13.sav

; -----

; -----

pl sh

14 Meter Pile – 2.5 Discharge Opening

```
;fname: briansPFC14-2.5.DAT
; Height=14
new
; -----
def make_walls ; create walls: 5 plate floor
  wall_kn= 1e10

command
  wall id=6 type cylinder end1 0 0 -1 end2 0 0 14 rad 17.605 kn=wall_kn
end_command

command
  wall id=7 type cylinder end1 0 0 -2 end2 0 0 -14 rad 14.0 14.0 kn=wall_kn
end_command

  _x0 = 15
  _y0 = 15
  _z0 = -14
  _x1 = -15
  _y1 = 15
  _z1 = -14
  _x2 = -15
  _y2 = -15
  _z2 = -14
  _x3 = 15
  _y3 = -15
  _z3 = -14
command
  wall id=8 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) (_x3,_y3,_z3)
end_command

  _x0 = 19
  _y0 = 19
  _z0 = 0
  _x1 = -19
  _y1 = 19
  _z1 = 0
  _x2 = -19
  _y2 = 1.25
  _z2 = 0
  _x3 = 19
  _y3 = 1.25
  _z3 = 0
command
  wall id=1 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
  (_x3,_y3,_z3)
```

```
end_command
```

```
_x0 = -1.25  
_y0 = 2  
_z0 = 0  
_x1 = -19  
_y1 = 2  
_z1 = 0  
_x2 = -19  
_y2 = -2  
_z2 = 0  
_x3 = -1.25  
_y3 = -2  
_z3 = 0
```

```
command
```

```
  wall id=2 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &  
    (_x3,_y3,_z3)  
end_command
```

```
_x0 = 19  
_y0 = -1.25  
_z0 = 0  
_x1 = -19  
_y1 = -1.25  
_z1 = 0  
_x2 = -19  
_y2 = -19  
_z2 = 0  
_x3 = 19  
_y3 = -19  
_z3 = 0
```

```
command
```

```
  wall id=3 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &  
    (_x3,_y3,_z3)  
end_command
```

```
_x0 = 19  
_y0 = 2  
_z0 = 0  
_x1 = 1.25  
_y1 = 2  
_z1 = 0  
_x2 = 1.25  
_y2 = -2  
_z2 = 0  
_x3 = 19  
_y3 = -2  
_z3 = 0
```

```

command
  wall id=4 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

```

_x0 = 2
_y0 = 2
_z0 = 0
_x1 = -2
_y1 = 2
_z1 = 0
_x2 = -2
_y2 = -2
_z2 = 0
_x3 = 2
_y3 = -2
_z3 = 0

```

```

command
  wall id=5 kn=wall_kn face (_x0,_y0,_z0) (_x1,_y1,_z1) (_x2,_y2,_z2) &
    (_x3,_y3,_z3)
end_command

```

end

;-----

```

def particle_create
  s_stiff=0.0 ; initial stiffnesses
  n_stiff=1e6
  tot_vol = (1.0/3.0)* pi * (rad^2.0) * height
  rbar = 0.5 * (rlo + rhi)
  num = int((1.0 - poros) * tot_vol / (4.0 / 3.0 * pi * rbar^3))
  mult = 1.6 ; initial radius multiplication factor
  rlo_0 = rlo / mult
  rhi_0 = rhi / mult
  command
    gen id=1,num rad=rlo_0,rhi_0 x=-16.431,16.431 y=-16.431,16.431 z=0.0,height &
      filter ff_outlet tries 3000000
    prop dens=500 ks=s_stiff kn=n_stiff
  end_command
  ii = out(string(num)+' particles were created')
  sum = 0.0 ; get actual porosity
  bp = ball_head
  loop while bp # null
    sum = sum + 4.0 / 3.0 * pi * b_rad(bp)^3
    bp = b_next(bp)
  end_loop
  pmeas = 1.0 - sum / tot_vol
  mult = ((1.0 - poros) / (1.0 - pmeas))^(1.0/3.0)
  command

```

```

ini rad mul mult
; cycle 1000 =====
; prop ks=0.5e6 fric 0.4 =====
prop ks=0.5e6 fric 1000
end_command
end
; -----
def ff_outlet
ff_outlet = 0
_brad = fc_arg(0)
_bx = fc_arg(1)
_by = fc_arg(2)
_bz = fc_arg(3)
_rad = sqrt(_bx^2 + _by^2)
if (_rad + _brad) > abs(((14 - (_bz + _brad)) / tan(.2222*pi))) then
ff_outlet = 1
end_if
end
; -----
macro zero 'ini xvel 0 yvel 0 zvel 0 xspin 0 yspin 0 zspin 0'
SET height=14 rad=16.431 rlo=0.1 rhi=.35 poros=0.40

make_walls
particle_create
plot create assembly
plot set cap size 25
plot set mag 1.5
plot set rot 0 0 40
plot add ball lorange

pl add wa wire on

pl sh

pause
save example_1-1-brian.SAV
; -----
; restore example_1-1-brian.sav
; -----
; HISTORY
; -----
;
history b xp 0 0 14.00 ;id=1
history b yp 0 0 14.00 ;id=2
history b zp 0 0 14.00 ;id=3
history b xv 0 0 14.00 ;id=4
history b yv 0 0 14.00 ;id=5
history b zv 0 0 14.00 ;id=6

```

```

;
history b xp 0.234 0 13.80 ;id=7
history b yp 0.234 0 13.80 ;id=8
history b zp 0.234 0 13.80 ;id=9
history b xv 0.234 0 13.80 ;id=10
history b yv 0.234 0 13.80 ;id=11
history b zv 0.234 0 13.80 ;id=12
;
history b xp -0.234 0 13.80 ;id=13
history b yp -0.234 0 13.80 ;id=14
history b zp -0.234 0 13.80 ;id=15
history b xv -0.234 0 13.80 ;id=16
history b yv -0.234 0 13.80 ;id=17
history b zv -0.234 0 13.80 ;id=18
;
history b xp 0 0.234 13.80 ;id=19
history b yp 0 0.234 13.80 ;id=20
history b zp 0 0.234 13.80 ;id=21
history b xv 0 0.234 13.80 ;id=22
history b yv 0 0.234 13.80 ;id=23
history b zv 0 0.234 13.80 ;id=24
;
history b xp 0 -0.234 13.80 ;id=25
history b yp 0 -0.234 13.80 ;id=26
history b zp 0 -0.234 13.80 ;id=27
history b xv 0 -0.234 13.80 ;id=28
history b yv 0 -0.234 13.80 ;id=29
history b zv 0 -0.234 13.80 ;id=30
;
history b xp 0.469 0 13.60 ;id=31
history b yp 0.469 0 13.60 ;id=32
history b zp 0.469 0 13.60 ;id=33
history b xv 0.469 0 13.60 ;id=34
history b yv 0.469 0 13.60 ;id=35
history b zv 0.469 0 13.60 ;id=36
;
history b xp -0.469 0 13.60 ;id=37
history b yp -0.469 0 13.60 ;id=38
history b zp -0.469 0 13.60 ;id=39
history b xv -0.469 0 13.60 ;id=40
history b yv -0.469 0 13.60 ;id=41
history b zv -0.469 0 13.60 ;id=42
;
history b xp 0 0.469 13.60 ;id=43
history b yp 0 0.469 13.60 ;id=44
history b zp 0 0.469 13.60 ;id=45
history b xv 0 0.469 13.60 ;id=46
history b yv 0 0.469 13.60 ;id=47

```

```

history b zv 0 0.469 13.60 ;id=48
;
history b xp 0 -0.469 13.60 ;id=49
history b yp 0 -0.469 13.60 ;id=50
history b zp 0 -0.469 13.60 ;id=51
history b xv 0 -0.469 13.60 ;id=52
history b yv 0 -0.469 13.60 ;id=53
history b zv 0 -0.469 13.60 ;id=54
;
history b xp 0.704 0 13.40 ;id=55
history b yp 0.704 0 13.40 ;id=56
history b zp 0.704 0 13.40 ;id=57
history b xv 0.704 0 13.40 ;id=58
history b yv 0.704 0 13.40 ;id=59
history b zv 0.704 0 13.40 ;id=60
;
history b xp -0.704 0 13.40 ;id=61
history b yp -0.704 0 13.40 ;id=62
history b zp -0.704 0 13.40 ;id=63
history b xv -0.704 0 13.40 ;id=64
history b yv -0.704 0 13.40 ;id=65
history b zv -0.704 0 13.40 ;id=66
;
history b xp 0 0.704 13.40 ;id=67
history b yp 0 0.704 13.40 ;id=68
history b zp 0 0.704 13.40 ;id=69
history b xv 0 0.704 13.40 ;id=70
history b yv 0 0.704 13.40 ;id=71
history b zv 0 0.704 13.40 ;id=72
;
history b xp 0 -0.704 13.40 ;id=73
history b yp 0 -0.704 13.40 ;id=74
history b zp 0 -0.704 13.40 ;id=75
history b xv 0 -0.704 13.40 ;id=76
history b yv 0 -0.704 13.40 ;id=77
history b zv 0 -0.704 13.40 ;id=78
;
history b xp 0.938 0 13.20 ;id=79
history b yp 0.938 0 13.20 ;id=80
history b zp 0.938 0 13.20 ;id=81
history b xv 0.938 0 13.20 ;id=82
history b yv 0.938 0 13.20 ;id=83
history b zv 0.938 0 13.20 ;id=84
;
history b xp -0.938 0 13.20 ;id=85
history b yp -0.938 0 13.20 ;id=86
history b zp -0.938 0 13.20 ;id=87
history b xv -0.938 0 13.20 ;id=88

```

```

history b yv -0.938 0 13.20 ;id=89
history b zv -0.938 0 13.20 ;id=90
;
history b xp 0 0.938 13.20 ;id=91
history b yp 0 0.938 13.20 ;id=92
history b zp 0 0.938 13.20 ;id=93
history b xv 0 0.938 13.20 ;id=94
history b yv 0 0.938 13.20 ;id=95
history b zv 0 0.938 13.20 ;id=96
;
history b xp 0 -0.938 13.20 ;id=97
history b yp 0 -0.938 13.20 ;id=98
history b zp 0 -0.938 13.20 ;id=99
history b xv 0 -0.938 13.20 ;id=100
history b yv 0 -0.938 13.20 ;id=101
history b zv 0 -0.938 13.20 ;id=102
;
history b xp 1.17 0 13.00 ;id=103
history b yp 1.17 0 13.00 ;id=104
history b zp 1.17 0 13.00 ;id=105
history b xv 1.17 0 13.00 ;id=106
history b yv 1.17 0 13.00 ;id=107
history b zv 1.17 0 13.00 ;id=108
;
history b xp -1.17 0 13.00 ;id=109
history b yp -1.17 0 13.00 ;id=110
history b zp -1.17 0 13.00 ;id=111
history b xv -1.17 0 13.00 ;id=112
history b yv -1.17 0 13.00 ;id=113
history b zv -1.17 0 13.00 ;id=114
;
history b xp 0 1.17 13.00 ;id=115
history b yp 0 1.17 13.00 ;id=116
history b zp 0 1.17 13.00 ;id=117
history b xv 0 1.17 13.00 ;id=118
history b yv 0 1.17 13.00 ;id=119
history b zv 0 1.17 13.00 ;id=120
;
history b xp 0 -1.17 13.00 ;id=121
history b yp 0 -1.17 13.00 ;id=122
history b zp 0 -1.17 13.00 ;id=123
history b xv 0 -1.17 13.00 ;id=124
history b yv 0 -1.17 13.00 ;id=125
history b zv 0 -1.17 13.00 ;id=126
;
history b xp 2.34 0 12.00 ;id=127
history b yp 2.34 0 12.00 ;id=128
history b zp 2.34 0 12.00 ;id=129

```

```

history b xv 2.34 0 12.00 ;id=130
history b yv 2.34 0 12.00 ;id=131
history b zv 2.34 0 12.00 ;id=132
;
history b xp -2.34 0 12.00 ;id=133
history b yp -2.34 0 12.00 ;id=134
history b zp -2.34 0 12.00 ;id=135
history b xv -2.34 0 12.00 ;id=136
history b yv -2.34 0 12.00 ;id=137
history b zv -2.34 0 12.00 ;id=138
;
history b xp 0 2.34 12.00 ;id=139
history b yp 0 2.34 12.00 ;id=140
history b zp 0 2.34 12.00 ;id=141
history b xv 0 2.34 12.00 ;id=142
history b yv 0 2.34 12.00 ;id=143
history b zv 0 2.34 12.00 ;id=144
;
history b xp 0 -2.34 12.00 ;id=145
history b yp 0 -2.34 12.00 ;id=146
history b zp 0 -2.34 12.00 ;id=147
history b xv 0 -2.34 12.00 ;id=148
history b yv 0 -2.34 12.00 ;id=149
history b zv 0 -2.34 12.00 ;id=150
;
history b xp 3.52 0 11.00 ;id=151
history b yp 3.52 0 11.00 ;id=152
history b zp 3.52 0 11.00 ;id=153
history b xv 3.52 0 11.00 ;id=154
history b yv 3.52 0 11.00 ;id=155
history b zv 3.52 0 11.00 ;id=156
;
history b xp -3.52 0 11.00 ;id=157
history b yp -3.52 0 11.00 ;id=158
history b zp -3.52 0 11.00 ;id=159
history b xv -3.52 0 11.00 ;id=160
history b yv -3.52 0 11.00 ;id=161
history b zv -3.52 0 11.00 ;id=162
;
history b xp 0 3.52 11.00 ;id=163
history b yp 0 3.52 11.00 ;id=164
history b zp 0 3.52 11.00 ;id=165
history b xv 0 3.52 11.00 ;id=166
history b yv 0 3.52 11.00 ;id=167
history b zv 0 3.52 11.00 ;id=168
;
history b xp 0 -3.52 11.00 ;id=169
history b yp 0 -3.52 11.00 ;id=170

```

```

history b zp 0 -3.52 11.00 ;id=171
history b xv 0 -3.52 11.00 ;id=172
history b yv 0 -3.52 11.00 ;id=173
history b zv 0 -3.52 11.00 ;id=174
;
history b xp 4.69 0 10.00 ;id=175
history b yp 4.69 0 10.00 ;id=176
history b zp 4.69 0 10.00 ;id=177
history b xv 4.69 0 10.00 ;id=178
history b yv 4.69 0 10.00 ;id=179
history b zv 4.69 0 10.00 ;id=180
;
history b xp -4.69 0 10.00 ;id=181
history b yp -4.69 0 10.00 ;id=182
history b zp -4.69 0 10.00 ;id=183
history b xv -4.69 0 10.00 ;id=184
history b yv -4.69 0 10.00 ;id=185
history b zv -4.69 0 10.00 ;id=186
;
history b xp 0 4.69 10.00 ;id=187
history b yp 0 4.69 10.00 ;id=188
history b zp 0 4.69 10.00 ;id=189
history b xv 0 4.69 10.00 ;id=190
history b yv 0 4.69 10.00 ;id=191
history b zv 0 4.69 10.00 ;id=192
;
history b xp 0 -4.69 10.00 ;id=193
history b yp 0 -4.69 10.00 ;id=194
history b zp 0 -4.69 10.00 ;id=195
history b xv 0 -4.69 10.00 ;id=196
history b yv 0 -4.69 10.00 ;id=197
history b zv 0 -4.69 10.00 ;id=198
;
history b xp 5.86 0 9.00 ;id=199
history b yp 5.86 0 9.00 ;id=200
history b zp 5.86 0 9.00 ;id=201
history b xv 5.86 0 9.00 ;id=202
history b yv 5.86 0 9.00 ;id=203
history b zv 5.86 0 9.00 ;id=204
;
history b xp -5.86 0 9.00 ;id=205
history b yp -5.86 0 9.00 ;id=206
history b zp -5.86 0 9.00 ;id=207
history b xv -5.86 0 9.00 ;id=208
history b yv -5.86 0 9.00 ;id=209
history b zv -5.86 0 9.00 ;id=210
;
history b xp 0 5.86 9.00 ;id=211

```

```

history b yp 0 5.86 9.00 ;id=212
history b zp 0 5.86 9.00 ;id=213
history b xv 0 5.86 9.00 ;id=214
history b yv 0 5.86 9.00 ;id=215
history b zv 0 5.86 9.00 ;id=216
;
history b xp 0 -5.86 9.00 ;id=217
history b yp 0 -5.86 9.00 ;id=218
history b zp 0 -5.86 9.00 ;id=219
history b xv 0 -5.86 9.00 ;id=220
history b yv 0 -5.86 9.00 ;id=221
history b zv 0 -5.86 9.00 ;id=222
;
history b xp 7.04 0 8.00 ;id=223
history b yp 7.04 0 8.00 ;id=224
history b zp 7.04 0 8.00 ;id=225
history b xv 7.04 0 8.00 ;id=226
history b yv 7.04 0 8.00 ;id=227
history b zv 7.04 0 8.00 ;id=228
;
history b xp -7.04 0 8.00 ;id=229
history b yp -7.04 0 8.00 ;id=230
history b zp -7.04 0 8.00 ;id=231
history b xv -7.04 0 8.00 ;id=232
history b yv -7.04 0 8.00 ;id=233
history b zv -7.04 0 8.00 ;id=234
;
history b xp 0 7.04 8.00 ;id=235
history b yp 0 7.04 8.00 ;id=236
history b zp 0 7.04 8.00 ;id=237
history b xv 0 7.04 8.00 ;id=238
history b yv 0 7.04 8.00 ;id=239
history b zv 0 7.04 8.00 ;id=240
;
history b xp 0 -7.04 8.00 ;id=241
history b yp 0 -7.04 8.00 ;id=242
history b zp 0 -7.04 8.00 ;id=243
history b xv 0 -7.04 8.00 ;id=244
history b yv 0 -7.04 8.00 ;id=245
history b zv 0 -7.04 8.00 ;id=246
;
history b xp 8.21 0 7.00 ;id=247
history b yp 8.21 0 7.00 ;id=248
history b zp 8.21 0 7.00 ;id=249
history b xv 8.21 0 7.00 ;id=250
history b yv 8.21 0 7.00 ;id=251
history b zv 8.21 0 7.00 ;id=252
;

```

```

history b xp -8.21 0 7.00 ;id=253
history b yp -8.21 0 7.00 ;id=254
history b zp -8.21 0 7.00 ;id=255
history b xv -8.21 0 7.00 ;id=256
history b yv -8.21 0 7.00 ;id=257
history b zv -8.21 0 7.00 ;id=258
;
history b xp 0 8.21 7.00 ;id=259
history b yp 0 8.21 7.00 ;id=260
history b zp 0 8.21 7.00 ;id=261
history b xv 0 8.21 7.00 ;id=262
history b yv 0 8.21 7.00 ;id=263
history b zv 0 8.21 7.00 ;id=264
;
history b xp 0 -8.21 7.00 ;id=265
history b yp 0 -8.21 7.00 ;id=266
history b zp 0 -8.21 7.00 ;id=267
history b xv 0 -8.21 7.00 ;id=268
history b yv 0 -8.21 7.00 ;id=269
history b zv 0 -8.21 7.00 ;id=270
;
; -----
; delete wall 5 ; ++++++ switch order of grav wall delete =====
; set gravity 0 0 -9.81
; cycle 5000

his dia muf ; =====

set grav 0 0 -9.81; =====

cy 3000

save grav1.sav; =====
del wa 5; =====
cy 5000; =====

; -----
save brian14-2.5-1.sav

cycle 50000
save brian14-2.5-2.sav

cycle 50000
save brian14-2.5-3.sav

cycle 50000

```

save brian14-2.5-4.sav

cycle 50000
save brian14-2.5-5.sav

cycle 50000
save brian14-2.5-6.sav

cycle 50000
save brian14-2.5-7.sav

cycle 50000
save brian14-2.5-8.sav

cycle 50000
save brian14-2.5-9.sav

cycle 50000
save brian14-2.5-10.sav

cycle 50000
save brian14-2.5-11.sav

cycle 50000
save brian14-2.5-12.sav

cycle 50000
save brian14-2.5-13.sav

; -----

; -----

pl sh